The Karlsruhe Physics Course

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Abstract

The Karlsruhe Physics Course is an attempt to modernize the physics syllabus by eliminating obsolete concepts, by restructuring the contents and by extensively applying a new model, the substance model. The course has been used, tested and improved for several years and we believe that the time has come to make it known to a greater public. We introduce the structure which is underlying the course and discuss some consequences for the teaching of various subfields of physics.

1. Introduction

The amount of the physical knowledge is increasing steadily, whereas the teaching time remains essentially unchanged. This fact obviously requires a continuous effort of adjustment and reprocessing of our knowledge. In this article we shall report about such an effort: about a physics course which has been developed over the past 20 years at the Didactics Department of the University of Karlsruhe. Although the most elaborate version of the course is for the lower secondary school (Herrmann 1994, 1997, 1998a), the project was not just to write a new school book. The objective was to develop a new way of teaching physics, independent of the target group of learners. The course is now known under the name *Karlsruhe Physics Course*.

Although the course contains innovations in many details it can be said that its peculiarities are essentially based on three ideas:

1. The historical development of physics has taken an intricate path. When teaching, we impose on our students to follow this path although there are shorter and easier ways to reach the same goals (Herrmann and Job 1994-1998, Herrmann and Job 1996). We have tried to eliminate such historical burdens from the physics syllabus.

2. We have chosen a unified approach to science teaching, based upon a certain class of quantities, which play a fundamental role in classical and modern physics: the extensive quantities energy, momentum, angular momentum, electric charge, amount of substance and entropy. When emphasizing extensive quantities the break-up of physics into sub-branches is nothing more than a classification of natural processes according to the extensive quantity playing the dominant role in each case. A knowledge of a single branch of physics already provides an analogy for the means by which processes are described in other branches including chemistry and biology (Herrmann 1998b).

3. We are extensively taking advantage of a model which, in the traditional curriculum, plays only a minor role: the substance model.

In the past few years this course had a considerable impact and other workers have been continuing and extending this line of work. An example is a university text book about thermodynamics by Fuchs (1996).

In no way do we want to claim that our proposal is a kind of definite solution. On the contrary, apart from presenting our own work, we would like to stimulate a debate about this approach and to encourage other efforts to drastically reduce the size of the physics syllabus.

In section 2 we shall comment about the manner in which our project has been carried out, and about the origin of the ideas underlying the course. In section 3, the structure of the course is presented. In section 4 the substance model is introduced and section 5 contains some of the specific consequences for various sub-fields as treated in the course.

2. General remarks

2.1 The project

All the parts of the course have been developed in essentially the same way. The first step was always to work on a restructuring of the subject independent of the kind of students to whom it might finally be destinated. Next, a version of a concrete course was realized for physics students at the university (Herrmann 1997). We never began with an elementary version. Otherwise, one could not be sure, that the result was solid enough to support the more advanced versions.

Only after having completed the university course, more elementary versions have been developed. The greatest amount of time has been invested in the development of a course for the lower secondary school. The first applications and tests of this high school version have been realized by ourselves, i. e. myself and other members of our university working group. For that purpose we were permanently teaching at a German High School. After several test runs at this school and after a complete written version had been realized, about 20 other professional school teachers took over the test work. Feed back was given to us in order to improve the new editions of the course. Until now an estimated number of 8000 pupils have run through the program. The tests have been strictly supervised by the school authority. During three years of intense observation no major difficulties arose and the school authorities gave their approbation for a general use of the concept in the High Schools of our Federal State (Baden-Württemberg). They also changed the teaching program in such a way that the Karlsruhe Physics Course can be used as an alternative to the traditional school books‡.

‡ "Dem vorliegenden Lehrplan liegt ein möglicher Aufbau für einen gymnasialen Physiklehrgang zugrunde. Wird die Physik unter anderen Gesichtspunkten, z. B. mit mengenartigen Größen, aufgebaut, so kann man mit den Begriffen Impuls und Entropie bereits in der Klasse 8 arbeiten. In diesem Fall können Inhalte der Lehrplaneinheit 1, Einführung in die Physik, durch andere geeignete Themen ersetzt werden. In der Lerhplaneinheit 2, Grundlagen der Mechanik, treten dann die statischen Aspekte zugunsten der dynamischen in den Hintergrund." Bildungsplan, Ministerium für Kultus und Sport, Baden-Württemberg, S. 286 (1994).

2.2 The origins

The Karlsruhe Physics Course contains numerous deviations from traditional physics courses. However, there is no innovation which does not have its roots in some previous work, sometimes in ideas of renowned scientists which have fallen into oblivion. We shall cite such sources in the following sections where it is suitable. There are a few sources, however, which we would like to accentuate and we shall mention them in advance.

1. We owe our knowledge about the analogy, which is so important for the conciseness of the course, to Falk's axiomatic treatment of thermodynamics (Falk 1968, Falk and Ruppel 1976, Falk 1990, Falk and Herrmann 1977 to 1982). Falk's work, on the other hand, can be seen to have its roots in the thermodynamics of W. J. Gibbs (1961). Essentially, the same analogy is also applied in many typical text books about the thermodynamics of irreversible processes: the emphasizing of currents and forces, where by forces is meant a gradient of the energy-conjugated intensive variable, see for instance Callen (1985). The same analogy is also used by other authors as a basis of what is often called system physics (Burkhardt 1987) or system dynamics (Fuchs 1996, Maurer 1990, 1998).

2. The mechanics which is based on the interpretation of forces as momentum currents, has a tradition, which is, compared to the respectable age of classical mechanics, relatively young: The proposal to interpret a force as a momentum flow was made for the first time in 1908 by Max Planck (1908). This date is not accidental. With the publication of the theory of relativity three years before, it became clear that energy and momentum should be understood as basic quantities and not as derived from supposedly more fundamental quatities like mass, velocity and force. However, the considerable age and dignity of classical mechanics has thwarted that this up-to-date and simpler interpretation of forces gained admission into the elementary text books. As far as we know, the first efforts in this respect are due to Di Sessa (1980) and to ourselves (Herrmann 1979).

In advanced texts, in particular in texts about hydrodynamics, this interpretation is customary since its first publication by Planck, see for instance Pauli (1963) or Landau and Lifshitz (1959).

3. We owe the idea that the common language concept of heat matches perfectly the properties of the physical quantity entropy to the work of G. Job (1972). Job himself, when he published his "Neudarstellung", was still unaware that the same idea had been presented in full clearness a long time ago in a paper by Callendar (1911), which apparently had been forgotten since.

4. Our treatment of the chemical potential as a universal driving force for all those processes where the quantity "amount of substance" is created, destroyed or transported is also due to Job (1978, 1981a, 1981b).

2.3 System dynamics modelling tools

In the same period of time when we developed our physics with substance-like quantities a new type of computer software was developed and improved, which perfectly fits into doing this kind of physics and which sometimes is referred to as system dynamics modelling tools. Examples of such programs are Stella (High Performance Systems, Inc., Hanover, NH), Powersim (Powersim AS, Isdalsto, Norway) and Dynamo (Pugh-Roberts Associates, Cambridge MA).

Modelling software is now considered by many teachers and school authorities as an important learning tool and may soon get a place in many syllabuses.

3. The structure of the course

3.1 Substance-like quantities

In the Karlsruhe Physics Course, a certain class of physical quantities play the role of basic concepts: the extensive or, as we like to call them, substance-like quantities (Falk 1968, Falk 1977). Among the substance-like quantities are mass, energy, electric charge, amount of substance, momentum, angular momentum and entropy. Each extensive quantity X obeys a continuity equation, which, in its integral form, reads:

$$\frac{dX}{dt} = I_X + \Sigma_X \qquad (1)$$

The validity of such an equation allows us to interpret X as a measure of the amount of a substance or fluid, I_X as a current intensity of X (Herrmann 1986), and Σ_X as the production rate of X. By "interpret" we mean that we are applying a model when dealing with these quantities, the "substance model".

According to this model, the change of the value of X has two causes: On the one hand a production or destruction of X within the considered region of space and on the other a flow through its boundary surface. Thus, equation (1) establishes a balance of the quantity X. Equation (1) can be brought into a local form:

$$\frac{\partial \rho_X}{\partial t} = \mathrm{div}\, \boldsymbol{j}_X + \sigma_X$$

Here, ρ_X is the density of X, $\boldsymbol{j}_X$ the current density and σ_X the production density.

For some substance-like quantities, the term Σ_X, or σ_X respectively, is always equal to zero. These quantities can change their value within the region only by a flow through the boundary surface. They are called “conserved quantities”. Energy and electric charge are examples of conserved quantities. Accordingly, equation (1) reads for the electric charge:

$$\frac{dQ}{dt} = I$$

Here, I is the strength of the electric current. For the energy we get:

$$\frac{dE}{dt} = P$$

where P is the strength of the energy current or “power”.

Other substance-like quantites, such as entropy and amount of substance can change their value by production and/or destruction. Thus, a substance-like quantity is not necessarily a conserved quantity.

A substance-like quantity must not be scalar. Momentum and angular momentum are examples for vectorial substance-like quantities. If the coordinate system is kept fixed it is allowed to image a vectorial substance-like quantity as three scalar substance-like quantities, where for each of the three components a balance equation of the form (1) holds.

3.2 The analogy

When using the extensive quantities as a basis for structuring the course, one can take advantage of a far-reaching analogy between the various parts of physics, including chemistry if the quantity “amount of substance” is added to the list of substance-like quantities.

Table 1.

extensive quantity	**conjugate intensive quantity**	**current**	**subfield of science**	**energy flow**
electric charge Q	electric potential φ	electric current I	electricity	$P = U \cdot I$
momentum $\boldsymbol{p}$	velocity $\boldsymbol{v}$	force F	mechanics	$P = \boldsymbol{v} \cdot \boldsymbol{F}$
entropy S	absolute temperature T	entropy current I_S	thermodynamics	$P = T \cdot I_S$
amount of substance n	chemical potential μ	substance current I_n	chemistry	$P = \mu \cdot I_n$

According to Table 1 the extensive quantities electric charge Q, momentum $\boldsymbol{p}$, entropy S and amount of substance n correspond to each other. The same holds true for the conjugated intensive quantities electric potential φ, velocity $\boldsymbol{v}$, absolute temperature T and chemical potential μ. To each of the extensive quantities a flow or current exists: the electric current I, the momentum current or force $\boldsymbol{F}$ (Herrmann and Schmid 1984, Herrmann and Schmid 1985a, Herrmann et al 1987), the entropy current I_S and the substance current I_n.

Many of the relationships that exist between the quantities of one subfield of science (one line in the table) have a counterpart in another subfield. An example is shown in the last column of Table 1. Each of the equations in this column represents a description of an energy transport. It is customary to say that energy is transmitted in one or the other “form”, according to which of the Equations describes the transmission (Falk 1968). The first equation (second line) corresponds to the so-called electric energy. (The letter U stand for an electric potential difference.) If the pertinent relation is that of the third line, then the energy exchange is called “work”. The equation of the forth line describes a transport in the form of heat and that of the last line corresponds to chemical energy.

There are quantities which have to be translated into themselves when applying the analogy of Table 1: On the one hand the kinematic quantities time and position, and on the other the energy. Thus, among the substance-like quantities, the energy plays a prominent part. The energy is not characteristic for any of the physical subfields. It is equally important in all of them. It plays the role of a unifying concept.

4. The substance model

The particle model is probably the best-known and most successful model of classical physics. However, among the models currently in use, there is another one, which also has a long history, but which never received the same kind of recognition as the particle model. It even does not have an established name. We propose to call it the “substance model”. As this name suggests, some physical object is imagined to be a fluid or substance or, in more colloquial terms, a “stuff”. Here, the concept of substance is to be understood in its common language meaning. An old example for the application of this model is to picture the electric charge as a substance or fluid. Hence, the name electric “current” for the quantity I.

We propose to make extensive use of this model, and not to limit it to those cases where it has been employed traditionally. We shall discuss three very distinct modes of application of the substance model. The first application consists in comparing extensive physical quantities with substances. The second is that fields are considered as substances and, in our third application we interpret as the density of a substance what currently is called the density of the probability of finding a particle at a point.

Notice, that when comparing a certain amount of an extensive quantity, a portion of the electromagnetic field or a certain amount of the square of the wave function with a substance, we do not claim that these entities are substances. All we do, is apply a model. A model, however, is never correct or false. A model can only be more or less appropriate.

4.1 Physical quantities in the substance model

When introducing a new physical quantity the student has to learn, among other things, the verbal “environment” of the quantity: verbs, adjectives, adverbs and prepositions which go together with the quantity. When formulating sentences with the quantities “force”, “work” or “electric potential difference” there is not much freedom: a force “acts on a body” or is “exerted by a body”, work is “realized” or “performed” and an electric potential difference “exists” or “is applied”.

On the contrary, when dealing with substance-like quantities it is correct to use all those figures of speech which are used when speaking about a substance. Thus, it is appropriate to say, that a body *contains* a certain amount of electric charge, but also that the charge *sits on* the body. Electric charge can *flow* from one place to another. It can be *accumulated*, *concentrated*, *diluted*, *distributed*, *lost*, *collected* and much more. The explanation of where the great freedom in the use of the language comes from, is that we are applying the substance-model. Every student is familiar with this language already before his or her first science lesson. Emphasizing the substance-like character of these quantities represents a substantial aid when teaching science.

In the traditional teaching of science one not always takes advantage of this possiblity. Usually, the substance model is only applied when dealing with the quantities mass and electric charge. Energy, entropy and momentum, on the contrary, are derived from other quantities. By doing so, the insight that they are substance-like is hampered.

The substance model for extensive quantities can be extended in such a way that it also includes the corresponding intensive quantities. Let us explain this claim again with the example of electricity. Suppose an electric current is flowing through what is called a resistor. The word resistor belongs already to the substance model. The word suggests that this device opposes to the flow of electricity. In order to flow, a kind of driving force is needed, an electric potential difference or electric tension. Thus, the potential difference appears as the cause, and the electric current as the effect. Let us show the arbitrariness of this wording with the help of the special case of Ohm's law:

$U = R \cdot I.$

The equation tells us, that U and I are proportional to one another. It does not tell us anything about which quantity is the cause and which is the effect. We feel it more natural to call the potential difference the cause, but the reason is simply, that in most cases on a power supply we adjust the voltage and not the current. Indeed, when running the power supply in the current stabilized mode, it is more natural to say, that the current causes a potential drop: The current is the cause, the potential difference the effect.

In spite of its arbitrariness, the substance model has proved to be extraordinary useful for the teaching of electricity. The learner can orient himself by means of those phenomena from which the model stems: currents of water or other fluids.

However, the real power of the model comes from the fact that it not only applies to electricity but also to other extensive quantities. Just as an electric potential difference can be interpreted as a driving force for a current of electric charge, a temperature difference can be considered as the cause of an entropy current, a chemical potential difference is necessary to drive a substance current and a velocity difference is responsible for a momentum current. (The momentum which a car looses due of the friction, is increasing with the speed of the car.) There is a great advantage in teaching economy when using the picture not only for electricity but also for other dissipative transport phenomena.

Finally, we propose one further extension of the substance model. The equations in the last column of Table 1 suggest a simple picture for the description of an energy transport: We call the substance-like quantity which is flowing simultaneously with the energy according to Eqs. (3), the energy carrier (Falk and Herrmann 1981, Falk et al 1983). Thus, the energy is carried by momentum, electric charge, entropy or amount of substance. In a device which in traditional terms is called an energy converter the energy simply changes its carrier. It enters with one carrier, is then “transshipped” to a second carrier and leaves the device with this new carrier.

When teaching mechanics or thermodynamics traditionally, one encounters problems which are said to be related to false preconceptions or misconceptions of the students. Instead of changing the students' ideas such that they conform with the way physics is presented, one could also think about finding a presentation of physics, which conforms better with the way people are reasoning in everyday life situations. The use of the substance model has turned out to be a step in this direction (Pozzo et al 1997).

4.2 Fields in the substance model

Usually, fields are introduced as very particular creatures. It is said that a field is a region of space with certain properties, or that an electric field is the space around a charged body. Actually, this way of speaking evokes the impression that the concept of a field is rather mysterious. It is suggested that a field is a portion of empty space with certain properties or, even worse, a kind of nothing with properties.

Actually, there is no reason for such a mystification. A field is a physical system. As any other physical system, it can admit various states and in each state the physical standard variable have certain values (Falk 1968 p. 54, Herrmann 1989). Just as any other physical object, an electromagnetic field has energy, momentum, entropy and pressure (or mechanical stress). In certain states it has a temperature and a chemical potential. When speaking about a field, there is no reason to apply a different wording as when speaking about a material system, a gas for instance.

In order to explain to somebody what is air, it would be perfectly correct to say air is a portion of space with certain properties, but it would not be a very suggestive explanation. The same holds true for a field. Instead of introducing a field as a portion of space with certain properties, it is clearer to say a field is an object with these properties. Actually, when speaking in this way, we are employing the substance model.

However, in order to fully profit from this model, we have to complement the language. We need one name for the object under consideration and another name for the material the object is made of. For the first concept a name exists already: field. For the second, in traditional physics there is no name. As a provisional name, in the Karlsruhe Physics Course we use the word “field stuff” (in German “Feldstoff”).

4.3 Electrons in the substance model

Atoms are usually introduced as consisting of a nucleus and an electron shell. This introduction mostly begins with the creation of a cognitive conflict. It is said, that an electron is a small object which is *moving* around the nucleus, but which does not have a trajectory. To avoid this conflict we have chosen a model in which the elctron does not move as long as its state is an eigen state of the energy. According to this model, the nucleus is surrounded by a substance which we call *electronium*. The density of the electronium is what normally is called the electron density or the density of the probability for finding the electron at the point under consideration, i. e. for one-electron systems the square of the wave function. That density of the electronium is what is currently determined by means of X-ray diffraction techniques. According to this model, an electron is an elementary portion of the electronium: a portion with a charge of $1.6 \cdot 19^{-19}$ C. Thus, an electron, although having a definite charge and mass, has not a unique shape and extension. Its shape is the same as that of the square of the wave function and thus depends on the state of the electron.

5. The course

In this section, some of the consequences of the general ideas described so far for the concrete design of the course are outlined. However, it is not a summary of the contents of the course.

5.1 Mechanics

According to our basic structure, momentum is the central quantity of mechanics. It can be used to define what mechanics is: that part of physics which deals with momentum and its currents (and later with angular momentum and its currents). Therefore, it is natural to introduce momentum at the very beginning of the mechanics part. It is introduced operationally by a measuring method (Herrmann and Schubart 1989). For an intuitive understanding, momentum is introduced as a measure of the content of movement of a body, what in colloquial terms would be called the “force”, the “power” or the “impetus” of a body‡. Since it is a fundamental quantity we give a proper name to its SI unit: 1 Ns is called 1 Huygens (abbreviated Hy).

‡Actually, all of our teaching experience was done with German pupils. The common language words which they proposed were typically: "Schwung", "Kraft", "Wucht" and the English word "Power" – a word which is well-known to German youngsters. Notice that the word "Kraft" (in English "force") has, in common language, a much wider meaning than in physics. Moreover, the correspondence with the physical concept of momentum seems to be better than that with the physicist's force.

Momentum can go or flow from one body to another. Spontaneously, i. e. in a frictional or dissipative process, it flows from the body with a higher velocity to the one with the lower velocity. In order to get it in the direction opposite to this natural tendency one needs what we like to call a momentum pump. Often, a motor is used as a momentum pump.

Newton's laws, when formulated with momentum currents, reveal to be no more than the expression of momentum conservation. Since the conservation of momentum is presupposed to be valid from the beginning (just as in electricity the conservation of the electric charge is currently taken for granted) a formulation of Newton's laws is not necessary anymore (Herrmann and Schmid 1985b).

Friction is, in our approach, not an unwanted phenomenon, which only disturbs in the realm of pure Newtonian mechanics. It is a most natural process, in which momentum passes dissipatively from one body to another. Thus, the rectilinear movement of a car on a highway appears as a steady state or flow equilibrium: The momentum which its motor is steadily pumping into the car is equal to the momentum flowing out into the air and into the earth, due to friction processes.

5.2 Thermodynamics

Just as mechanics begins with momentum, thermodynamics begins with the introduction of entropy. The intuitive understanding which we are stimulating is that entropy is what in colloquial terms would be called heat or amount of heat. (Callendar 1911, Job 1972, Falk 1985, Fuchs 1986, Fuchs 1987, Fuchs 1996). Just as momentum, also entropy gets its own SI unit: 1 J/K is called 1 Carnot (abbreviated Ct). This is an old proposal by Callendar (1911). It is stated that a body at zero Kelvin has an entropy content of 0 Ct, or in more colloquial terms: An absolutely cold body does not contain heat. Entropy can be produced. It is produced in processes which represent a kind of friction: mechanical friction, electric "friction" in an electric resistor, or chemical "friction" in a free running chemical reaction. The second principle is formulated in the following way: Entropy can be produced but not destroyed.

Entropy flows spontaneously from a body of higher to a body of lower temperature. Since this is also a kind of frictional process, new entropy is produced in this process.

In order to get an entropy flow in the direction opposite to its natural tendency one needs an entropy pump, technically called a heat pump.

5.3 Electricity

The structure of electricity did not experience major changes in our course since in the traditional courses the substance model is already used. Electric charge is flowing spontaneously from places of higher to places of lower electric potential, and in order to get it flowing against this natural tendency an "electricity pump" is necessary: a battery or a generator or a solar cell.

The magnetic field is then introduced as a very concrete thing which sticks to magnetic poles and to current-carrying conductors.

5.4 Reactions

The course also contains a chapter about physical chemistry and this chapter has also the same structure as mechanics, heat and electricity (Job 1978, Job 1981a, Job 1981b). Just as an electric potential difference acts as a driving force of an electric current, a chemical potential difference causes a chemical reaction to run, to make a substance change its phase or to drive a diffusion current. In analogy to the electric resistance we introduce a chemical or reaction resistance. A catalyzer then appears as a switch which allows to turn on and off a chemical reaction.

Combustion cell and electrolytical cell are introduced as devices, in which energy is transferred from the energy carrier amount of substance to the energy carrier electricity and vice versa.

5.5 Data

We have shown that in our course the energy plays the role of a structuring concept. There is yet another quantity with this structuring power: Shannon's amount of data. It is the unifying quantity of all those parts of science and technology which have to do with the transmission, processing and storage of data: optics, acoustics, electronics, computer science. Just as the analogy discussed previously, the analogy between energy and amount of data has a sound physical basis (Herrmann and Schmid 1986).

It is important that the rapidly developing domain of data transport, processing and storage does not appear as an appendix to electronics or as a subbranch of mathematics, as it is the case in various other teaching programs.

In our course, energy transmissions are classified according to the respective *energy carrier*. In the same manner we classify data transmissions according to the pertinent *data carrier* (Herrmann et al 1985, Herrmann and Schmälzle 1987).

6. Conclusions

The physics syllabus needs a continuous effort of modernization. In our opinion, physicists have neglected this task in the past to some extent. That is why the need of majopr changes have accumulated. With the Karlsruhe Physics Course we propose an example for such a change.

Although many students have gone through the course by now we are still not able to judge the results. An evaluation of the course for the lower secondary school based on a sample of about 1000 pupils is now under way (Starauschek). However, much more has to be done in order to know the consequences.

With the present paper we would like to motivate a greater public to participate in the discussion of this proposal as well as encourage the work on other alternatives.

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CD-ROM for MacOS, MS-DOS, WINDOWS and WINDOWS 95. The CD contains:

– reading software (Acrobate Reader)

– the German version of the Karlsruhe Physics Course

– the most important chapters in Spanish language

– selected publications in English and German

– a University version of the Karlsruhe Physics Course: lecture notes for mechanics, electricity, thermodynamics and optics, in German language.

The CD can be purchased at “Abteilung für Didaktik der Physik, Universität, 76128 Karlsruhe, Germany” for 10 €. It is also part of the paper version which appeared in the Aulis Verlag.

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Planck M 1908 Bemerkungen zum Prinzip der Aktion und Reaktion in der allgemeinen Dynamik *Phys. Z.* **9** 828-830 'Wie die Konstanz der Energie den Begriff der Energieströmung, so zieht notwendig auch die Konstanz der Bewegungsgröße den Begriff der "Strömung der Bewegungsgröße", oder kürzer gesprochen: der "Impulsströmung" nach sich. Denn die in einem bestimmten Raum befindliche Bewegungsgröße kann sich nur durch äußere Wirkungen, also nach der Theorie der Nahewirkung nur durch Vorgänge an der Oberfläche des Raumes ändern, also ist der Betrag der Änderung in der Zeiteinheit ein Oberflächenintegral, welches als die gesamte Impulsströmung in das Innere des Raumes hinein bezeichnet werden kann. [...] Der gesamte Impulsstrom in das Innere eines Raumes hinein, also die Zunahme der im Innern befindlichen Bewegungsgröße pro Zeiteinheit, ist gleich der resultierenden mechanischen Kraft, welche auf die gesamte in dem Raume befindliche Masse wirkt.'

Pozzo R, Concari S B and Grabois M 1998 Primer Taller Internacional sobre Didáctica de la Física Universitaria, 5-8 Febrero, Matanzas, Cuba