

# An up-to-date approach to physics

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(Received 4 November 1983; accepted for publication 20 December 1983)

A unified approach to science teaching based upon a certain class of quantities which play fundamental roles in classical and modern physics is introduced. These quantities share the property of being substance-like, that is, each can be pictured to be contained in bodies and to flow from one body to another like a kind of "stuff." Such quantities include, for example, energy (= mass), momentum, angular momentum, electric charge, particle number (= amount of substance), and entropy. When emphasizing substance-like quantities, the breakup of physics into sub-branches is nothing more than a classification of natural processes according to the substance-like quantity playing the dominant role in each case. The method of presentation, however, remains the same from one sub-branch to another: different natural processes can be simply visualized and quantitatively described according to the same formal rules in terms of the increasing, decreasing, and flowing of the respective substance-like quantities in each case. Thus knowledge of a single branch of physics already provides an analogy for the ways and means by which processes are described in other branches (including chemistry and biology) as well. These claims are illustrated with the help of a few simple examples.

## I. INTRODUCTION

This paper reports on an approach to physics under development in the Institut für Didaktik der Physik at the University of Karlsruhe, Karlsruhe, West Germany. Mechanical concepts such as particle and trajectory are not as fundamental to this approach as are certain quantities which play important roles in thermodynamics as well as in modern physics, for example, in quantum mechanics. These quantities share the properties that they are contained in bodies, generally in physical systems, and flow through space. They include, for example, mass (energy), electric charge, momentum, angular momentum, particle number (amount of substance), and entropy. This approach has already been implemented over the past several years beginning in elementary school with grades five and six and also beginning in the university at the freshman level. The school curriculum based upon this approach is projected to continue on through junior high school and the university curriculum is being extended through graduate school.

## II. SUBSTANCE-LIKE QUANTITIES

Traditionally mechanics is at the heart of physics teaching: a physical problem is considered to be understood, in principle at least, if it can be explained in mechanical terms. Accordingly, the world is described as being made up of particles (mass points) and their interactions. This picture is commonly called the atomistic picture of the world.

The new insights of relativity and quantum mechanics have done little to modify this basic conviction despite the fact that quantum mechanics precludes the primary classical concept of a particle as a distinguishable mass point which can be followed through space and time, i.e., which has a trajectory. For this reason, too strong an emphasis upon the abovementioned atomistic picture could hinder an easy understanding of modern physics.

Quantities predominant in quantum mechanics such as energy, momentum, angular momentum, electric charge, and particle number are more similar to the extensive quantities of thermodynamics than they are to basic Newtonian concepts such as the individual mass point and the

quantities which describe its trajectory. Of course energy, momentum, and angular momentum also appear in Newtonian mechanics but then only as convenient tools for calculation, not, however, as primary concepts. In Newtonian mechanics the primary quantities are trajectory, velocity, mass, and force, whereas momentum is nothing more than another name for the product of mass times velocity and energy is a certain constant of motion. In quantum mechanics energy and momentum are treated quite differently. This is most clearly demonstrated by the fact that both energy and momentum can be quantized whereas the quantities from which these are classically constructed, such as velocity and force, cannot.

These considerations indicate that it is tedious at best to get a logical understanding of modern physics in terms of the primary quantities of classical mechanics. For this reason, the Karlsruhe physics project is based upon the same class of quantities which belong to the primary quantities of quantum mechanics as well as to the extensive quantities of thermodynamics.

These quantities have something in common, namely, each can be thought to be contained in a physical system and flow from one system to another. Hence each can be pictured as a kind of "stuff." For this reason we call them *substance-like*. The substance-like quantities also include quantities which are not usually talked about in quantum mechanics, in particular, entropy.

The idea that a physical quantity is substance-like first appeared historically in connection with quantities like mass and electric charge. In the phenomena of heat, *two* substance-like quantities are manifest: energy and entropy.<sup>1</sup> Each is contained in a material body. It even makes sense to speak about the amount of energy  $E$  or entropy  $S$  contained within an arbitrary region of space. If a body or, in general, a region of space filled homogeneously with energy and entropy is divided in two, each half contains half the original total amount of  $E$  or  $S$ .

Energy obeys a general conservation law (the First Law of Thermodynamics). Entropy obeys a general law forbidding its destruction (the Second Law of Thermodynamics). These two statements mean (1) the amount of energy con-

tained within a body or, in general, within a region of space can only increase (decrease) if energy flows into (out of) the body or region in question; and (2) the amount of entropy contained within a body or, in general, within a region of space can only decrease if entropy flows out of the body or region. The amount of entropy can increase, however, either via the inflow of entropy into the body or region in question or by the local creation of entropy.

When we say a quantity  $A$  is substance-like, we mean several things at once, most of which are generally familiar from the traditional description of electric charge:

(1) A spatial density  $\rho_A$  exists such that the amount of  $A$  contained in an arbitrary region  $\mathcal{R}$  of space is given by the volume integral

$$A = \int_{\mathcal{R}} \rho_A dV. \quad (1)$$

Here  $dV$  is the volume element of  $\mathcal{R}$ .

(2) A current density  $\mathbf{j}_A$  exists such that the flow of  $A$  (the  $A$  current) through an oriented surface  $\mathcal{F}$  is given by the surface integral

$$I_A = \int_{\mathcal{F}} d\mathbf{f} \cdot \mathbf{j}_A. \quad (2)$$

Here  $d\mathbf{f}$  is the element of  $\mathcal{F}$ .

(3) A relation of the form

$$\frac{d}{dt} \rho_A + \nabla \cdot \mathbf{j}_A = \sigma_A \quad (3)$$

exists between the quantities  $\rho_A$  and  $\mathbf{j}_A$ . Here  $\sigma_A$  is the local source density of the quantity  $A$ .

For  $\sigma_A = 0$ , Eq. (3) is a continuity equation expressing the conservation of the quantity  $A$  in a local formulation. In terms of the integral quantities  $A$  and  $I_A$ , (3) can be rewritten with the help of Gauss's theorem in the form

$$\frac{d}{dt} A + I_A = \Sigma_A. \quad (4)$$

Here  $\Sigma_A$  is the rate at which the quantity  $A$  is created (negative creation = destruction) in the region  $\mathcal{R}$ .

Taking  $A$  as entropy shows that a substance-like quantity need not necessarily be conserved. However, the negative converse is always true: every locally conserved quantity is substance-like.

### III. ENERGY AND ENTROPY

The simple picture of energy and entropy as substances contained in space, like gases in a bottle, and which can flow from one region to another, is in sharp contrast to the difficulties one has in providing a picture of these quantities, in particular of entropy, in a traditional course of physics instruction. The origin of these difficulties lies in the attempt to understand energy and entropy in terms of the basic quantities of Newtonian mechanics. Of course, such an attempt is partially successful for energy because the particular ways by which energy appears in mechanical processes are relatively easy to derive in terms of basic Newtonian concepts. Nevertheless, in Newtonian mechanics, it remains difficult to see the substance-like nature of energy, i.e., the localization and flow of energy. Furthermore, understanding entropy on the basis of mechanics is an even more difficult task.

If one pictures energy and entropy as being substance-like, one naturally obtains a simple understanding of these

quantities and the ability to work with them as well. As an example in support of this claim, let us take a short look at the theory of heat. A central statement of this theory is that an entropy current  $I_S$  is always coupled to an energy current  $I_E$  according to

$$I_E = T I_S. \quad (5)$$

The factor  $T$  is the absolute temperature and measures, so to speak, how much energy is "carried" by the entropy current  $I_S$ , or how much energy the entropy current is "loaded with."<sup>3,4</sup>

Equation (5) takes a more familiar form if one considers the currents  $I_E$  and  $I_S$  in terms of the time-rates-of-change  $dE/dt$  and  $dS/dt$ , respectively, of the amounts of energy  $E$  and entropy  $S$  contained within a system. Then according to (4),  $I_E = -dE/dt$  and  $I_S = -dS/dt$  so that (5) can be rewritten as

$$dE = T dS. \quad (6)$$

This is better known as the Gibbs fundamental form<sup>5</sup> of a system all of whose independent extensive variables except  $S$  are held constant.

As a simple application of (5), we derive the thermal efficiency of a heat engine: an entropy current  $I_S(i)$  is considered to be flowing into the machine through an input channel, say, the walls of a boiler, labeled  $i$  (for simplicity let us take  $I_S$  and  $I_E$  here to stand for the absolute value of an entropy and energy current, respectively). Then the flow of energy  $I_E(i)$  accompanying this flow of entropy into the machine through  $i$  is  $T(i)I_S(i)$ . At the output channel  $o$ , say the walls of a condenser, an entropy current  $I_S(o)$  is leaving the machine along with the energy current  $T(o)I_S(o)$ . According to the Second Law of Thermodynamics, the entropy current cannot decrease while flowing through a machine operating steadily. Accordingly,  $I_S(o) - I_S(i) = I_S(\text{created}) \geq 0$ . Thus the difference between the flow of energy  $I_E(i)$  into and  $I_E(o)$  out of the machine along with the entropy currents  $I_S(i)$  and  $I_S(o)$ , respectively, is given by

$$\begin{aligned} I_E(i) - I_E(o) &= T(i)I_S(i) - T(o)I_S(o) \\ &= [T(i) - T(o)]I_S(i) - T(o)[I_S(o) - I_S(i)] \\ &= \frac{T(i) - T(o)}{T(i)} T(i)I_S(i) - T(o)I_S(\text{created}). \end{aligned} \quad (7)$$

Traditionally the energy current on the left-hand side of (7) is called the "work done" by the machine. The efficiency  $\eta$  of the machine is thus given by

$$\begin{aligned} \eta &= \frac{T(i)I_S(i) - T(o)I_S(o)}{T(i)I_S(i)} \\ &= \frac{T(i) - T(o)}{T(i)} - \frac{T(o)I_S(\text{created})}{T(i)I_S(i)}. \end{aligned} \quad (8)$$

The Carnot efficiency is given by the first term on the right-hand side of (8). This is the efficiency of a machine operating reversibly, i.e., in the limit that  $I_S(\text{created}) = 0$ . Equation (8) shows that the actual efficiency of a machine is always smaller than the Carnot efficiency by the "dissipated" energy current  $T(o)I_S(\text{created})$  divided by the inflowing energy current  $T(i)I_S(i) = I_E(i)$ . The above example shows that irreversibility is naturally included in this description.

With the help of a simple diagram, it is easy to get an

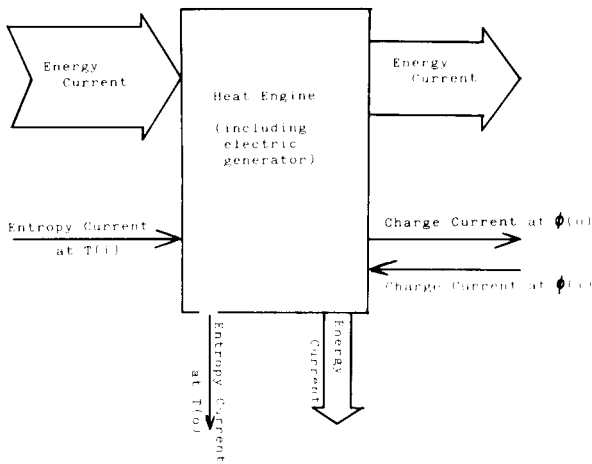


Fig. 1. Energy flow diagram for a heat engine including electric generator (see text for explanation of all symbols). The arrows represent the flow of energy, entropy, and electric charge through the respective channels into or out of the device. The outflow of entropy is at the temperature  $T(o) < T(i)$ . The outflow of electric charge is at the electric potential  $\phi(o) > \phi(i)$ .

overview of the inflow and outflow of energy and entropy from a heat engine along with the flow of electric charge if the engine is coupled to a generator (Fig. 1). In fact, such diagrams can be used to great advantage, not only for explaining heat engines, but also for explaining how every sort of energy conversion device or system works. This is easy to infer from the discussions in the next section.

#### IV. A WAY TO OTHER SUBSTANCE-LIKE QUANTITIES

We have chosen to investigate an example from thermodynamics for several reasons. First of all, thermodynamics provides many important rules for operating with substance-like quantities. Second, thermodynamics offers insight into how processes in other areas of physics can be treated with the help of substance-like quantities and their currents.

As an illustrating example, let us continue to consider heat engines. The energy current responsible for the “work done” by a machine is never accompanied by the flow of entropy from the machine but, rather, is accompanied by the flow of a substance-like quantity other than entropy. Indeed, one only need imagine several examples of different heat engines in order to see this:

(1) In a piston engine, the energy current usually called the “work done” flows through the piston rod. This energy current is accompanied by a *momentum current*<sup>6–8</sup> usually called “force.”

(2) If the energy current “work done” flows out of the machine through a turning and twisted shaft, this energy current is “accompanied” by the “torque” exerted by the drive shaft. This torque is an *angular momentum current*.<sup>9</sup> Accordingly, an angular momentum current accompanies the flow of energy out of the machine.

(3) If the machine is an aggregate comprised of turbine and generator, the energy current “work done” is accompanied by the flow of electric charge, i.e., by an *electric current*.

(4) Even if the heat engine is taken to be something as complex as a forest—the incoming flow of entropy  $I_S(i)$

enters this “machine” through the tree leaves—the energy current “work done” by this machine is accompanied by the flow (measured in moles/second) of a substance-like quantity leaving the machine, namely, by the flow of harvested trees and oxygen released from the forest (which flow is necessary if the forest is operating in a steady state).

#### V. ELECTRICITY

Of the above examples, the third is presumably the easiest to understand. The reason for this, of course, is that everybody is familiar with electric currents. Every physicist knows that electric charge is substance-like because, from the earliest days of his physics education, he got to know electric charge as an independent substance-like quantity: there is a charge density  $\rho_Q$  and a current density  $\mathbf{j}_Q$  such that the amount of charge contained in the region  $\mathcal{R}$  of space is given by (1) and the current  $I_Q$  through a surface  $\mathcal{F}$  is given by (2). Furthermore, Eqs. (3) and (4) hold with  $\sigma_Q = 0$  and  $\Sigma_Q = 0$ , respectively, since electric charge can be neither created nor destroyed.

There is also an analogy to (5), namely, the relation

$$I_E = \phi I_Q, \quad (9)$$

where  $\phi$  is the potential of the electric current.

In order to demonstrate the usefulness of (9), we consider an arbitrary electric device. Let the electric current flowing into the device be  $I_Q(i)$  and the current flowing out of the device  $I_Q(o)$ . Because of the general conservation of charge,  $I_Q(i) + I_Q(o) = 0$ . Accordingly, the net flow of energy through the device can be written as

$$\phi(o)I_Q(o) + \phi(i)I_Q(i) = [\phi(i) - \phi(o)]I_Q(i). \quad (10)$$

If  $\phi(o) > \phi(i)$ , the net flow of energy given by (10) is *out of* the device whereas, if  $\phi(i) < \phi(o)$ , the net flow of energy is *into* the device. Equation (10) is usually written in the form  $P = UI$  and reads as follows: The power  $P$  of the device is equal to the product of the potential difference  $U [= \phi(i) - \phi(o)]$  between the input and output channels of the device with the electric current  $I (= I_Q)$  flowing through the device.

As we see from this example, electricity is traditionally taught with an emphasis upon the substance-like quantity electric charge: electric charge plays a role in the description of electric phenomena similar to that which the substance-like quantity entropy plays in the description of thermal phenomena. One might therefore expect that the description of yet other areas of physics on the basis of substance-like quantities will to some extent be analogous to the familiar way electricity is traditionally treated.

#### VI. MECHANICS

Just as electric charge is so to speak characteristic of electricity, momentum is the characteristic substance-like quantity of mechanics. However, the substance-like nature of momentum is by no means obvious from a Newtonian point of view. This is because, in Newtonian mechanics, momentum is defined as the product of mass with velocity and the momentum current is even given an entirely different name: force.<sup>6,7</sup>

Strictly speaking, momentum  $\mathbf{p}$  is not one but rather a set of three independent substance-like quantities. Each of the three components  $p_x$ ,  $p_y$ , and  $p_z$  of  $\mathbf{p}$  separately obeys a conservation equation (4). Accordingly, the study of mechan-

ics is more difficult than the study of electricity since one must simultaneously keep track of three independent substance-like quantities.

Since momentum is conserved, the amount  $\mathbf{p}$  of momentum contained within the region  $\mathcal{R}$  of space occupied by a body can only change if a momentum current  $\mathbf{I}_p$  flows through the surface of the region  $\mathcal{R}$ . According to (4), the time-rate-of-change  $d\mathbf{p}/dt$  of the momentum contained in  $\mathcal{R}$  is connected to  $\mathbf{I}_p$  by the relation

$$\frac{d\mathbf{p}}{dt} + \mathbf{I}_p = 0. \quad (11)$$

A comparison of (11) with Newton's Second law

$$\frac{d\mathbf{p}}{dt} = \mathbf{F} \quad (12)$$

shows that a force  $\mathbf{F}$  is identical with a (negative) momentum current:  $\mathbf{F} = -\mathbf{I}_p$ . Thus Newton's Second law is the integral form of the continuity equation of momentum or, as we prefer to say, it is the *local formulation of momentum conservation*. Any change in the momentum of a body can only be affected by means of a momentum current penetrating the surface of the body.

Looking at Newton's Laws in this way, all three laws are statements about momentum conservation:

(1) Newton's First Law states that the amount of momentum contained within a body does not change as long as the net flow of momentum into or out of the body is zero.

(2) Newton's Second Law, as mentioned above, expresses the continuity equation for momentum.

(3) Newton's Third Law states that if a momentum current flows out of a body  $A$  and into a body  $B$ , the strength of the momentum current leaving  $A$  is equal to the strength of the momentum current entering  $B$ .

Newton's First Law, which includes the case when the momentum current through every surface element of a body vanishes, also includes the case when only the sum of the momentum currents through all, say  $N$ , surface elements of the body is zero:

$$\sum_{i=1}^N \mathbf{I}_{p_i} = 0. \quad (13)$$

Equation (13) is a kind of Kirchhoff's junction theorem describing momentum currents in the case of static equilibrium.<sup>8</sup> Because of the equality  $\mathbf{F} = -\mathbf{I}_p$ , Eq. (13) is identical to the familiar rule for constructing a free-body diagram in statics.

A relation analogous to (5) and (9) also exists in mechanics. It expresses the fact that a momentum current  $\mathbf{I}_p$  is coupled to an energy current  $I_E$  according to

$$I_E = \mathbf{v} \cdot \mathbf{I}_p \\ = v_x I_{p_x} + v_y I_{p_y} + v_z I_{p_z}. \quad (14)$$

Here the velocity  $\mathbf{v}$  expresses how much energy flows simultaneously with the momentum current, i.e., how much energy the momentum current is "loaded with."

Equation (14) is usually written in the form  $P = \mathbf{v} \cdot \mathbf{F}$ , where  $P$  is the power (= energy current) of a body moving at the instantaneous velocity  $\mathbf{v}$  while being acted upon by the force  $\mathbf{F}$ .

To get a picture of an application of (14), let us consider a familiar example: a momentum current  $-\mathbf{I}_p$  flowing into a body moving at the instantaneous velocity  $\mathbf{v}$ . According to (11),  $-\mathbf{I}_p = d\mathbf{p}/dt$  where  $\mathbf{p}$  is the momentum of the

body. In the same way,  $-I_E = dE/dt$  where  $E$  is the energy of the body and  $-I_E$  is the energy current flowing into the body. Accordingly, (14) can be rewritten in the form  $dE/dt = \mathbf{v} \cdot d\mathbf{p}/dt$ . However, since this relation is invariant with respect to substitutions of the time parameter  $t$  with any single-valued function  $t' = t'(t)$  (this can be seen by multiplying the relation through by  $dt/dt'$ ), this relation and, consequently, (14), can be rewritten as

$$dE = \mathbf{v} \cdot d\mathbf{p} \\ = v_x dp_x + v_y dp_y + v_z dp_z. \quad (15)$$

This is the Gibbs Fundamental Form for a moving body. It is valid in both nonrelativistic and relativistic mechanics when  $\mathbf{v}$  is taken to be the velocity of the body. Indeed, using the classical relation  $\mathbf{p} = m\mathbf{v}$  in (14) and integrating gives for the classical energy of a moving body

$$E = E_o + p^2/2m \\ = E_o + (m/2)v^2. \quad (16)$$

Similarly, using the relativistic relation  $\mathbf{p} = (E/c^2)\mathbf{v}$  in (15) and integrating results in the well-known relativistic formula

$$E = (E_o^2 + c^2 p^2)^{1/2} \\ = E_o / (1 - v^2/c^2)^{1/2}. \quad (17)$$

In looking back at the piston engine discussed above, it can be seen that the energy in the energy current "work done" is "carried" by the current of another substance-like quantity, namely, momentum: the force "exerted by the piston rod" is nothing other than this momentum current. It is clear that similar considerations can be carried out for a machine by which the energy current "work done" flows through a rotating twisted shaft: the torque "exerted by the shaft" is nothing other than the angular momentum current, that is, the flow of the substance-like quantity, angular momentum  $\mathbf{L}$  through the shaft. Just like momentum, angular momentum is comprised of three independent substance-like quantities, namely,  $L_x, L_y,$  and  $L_z$ . Similarly, there are equations analogous to (14) and (15) in which momentum  $\mathbf{p}$  is replaced by angular momentum  $\mathbf{L}$  and velocity  $\mathbf{v}$  by angular velocity  $\boldsymbol{\omega}$ .

## VII. REACTIONS

Just as the description of thermal, electrical, and mechanical processes can be based upon the flow of the substance-like quantities entropy  $S$ , charge  $Q$ , and momentum  $\mathbf{p}$  or angular momentum  $\mathbf{L}$ , respectively, processes by which matter or particle reactions take place can be described with the help of the quantity *amount of substance*  $n$ .<sup>10</sup> Such processes include chemical as well as nuclear or elementary particle processes; electric conduction phenomena in gases, liquids, and solids; processes in biological cells; and many other processes as well.

A few words are in order here concerning the quantity  $n$ . Because the amount of substance  $n$  is usually taken to be the "number of particles" involved in a process and, therefore, is often called "particle number," one may easily lose sight of the fact that  $n$  is actually a physical quantity (with its own units) and not "just" a number. Both thermodynamics and quantum mechanics require that  $n$  be viewed as a valid physical quantity of its own right. Indeed, the fact that the same physical quantity  $n$  known from thermody-

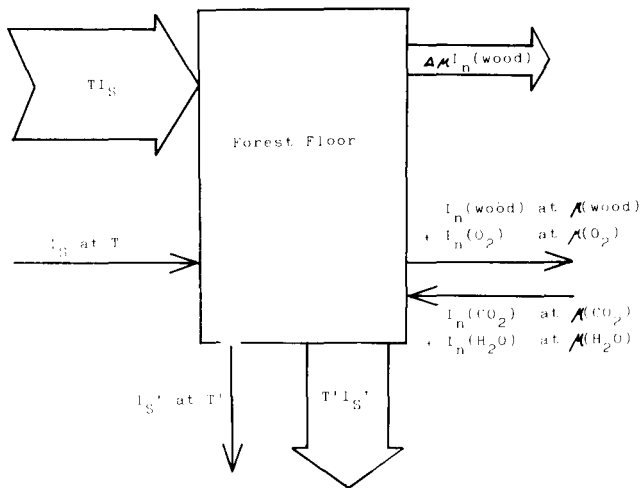


Fig. 2. Energy flow diagram for photosynthesis (see text for explanation of all symbols). If the horizontal arrows are exchanged, left for right, this becomes the energy flow diagram for a fire.

namics is quantized in quantum mechanics expresses the atomistic structure of the world.

The unit of the quantity  $n$  is the mole. Once again it should be emphasized that the word "mole" is not the name of the number  $6.02 \times 10^{23}$  just as "dozen" is not the name of the number 12; but, rather, that "mole" is a unit, just like "joule" or "coulomb." Furthermore, when speaking of a "particle," one is usually referring to a definite, namely the smallest, nonzero value which  $n$  can attain. This value is given by the "elementary unit amount":  $1.66 \times 10^{-24}$  mole. This value of  $n$  is just as valid a natural constant as is the value  $1.6 \times 10^{-19}$  coulomb, the "elementary unit charge." Since the quantity  $n$  is measured in moles, the dimension of an  $n$ -current is moles/s.

Figure 2 shows a flow diagram for the abovementioned machine "forest" operating in steady state. The following currents flow into the forest:

(1) An  $S$  current  $I_S$  (with sunlight). The current  $I_S$  is connected to an energy current  $TI_S$  where  $T$  is the absolute temperature of the surface of the sun ( $T \approx 6000$  K).

(2) An  $n$  current  $I_n(\text{CO}_2)$  of carbon dioxide gas as well as an  $n$  current  $I_n(\text{H}_2\text{O})$  of water. The former is connected to an energy current  $\mu(\text{CO}_2)I_n(\text{CO}_2)$ , the latter to an energy current  $\mu(\text{H}_2\text{O})I_n(\text{H}_2\text{O})$ . Both  $n$  currents together are connected to a total energy current  $\mu(\text{CO}_2)I_n(\text{CO}_2) + \mu(\text{H}_2\text{O})I_n(\text{H}_2\text{O})$ . The factors  $\mu(\text{CO}_2)$  and  $\mu(\text{H}_2\text{O})$  are measures of the extent to which the respective  $n$  currents  $I_n(\text{CO}_2)$  and  $I_n(\text{H}_2\text{O})$  are "loaded" with energy. Traditionally, these factors  $\mu(\text{CO}_2)$  and  $\mu(\text{H}_2\text{O})$  are called the *chemical potentials* of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , respectively.

The following currents flow out of the forest:

(1) An  $S$  current  $I_S' \geq I_S$ . This  $S$  current is connected to an energy current  $T'I_S'$  where  $T'$  is the absolute temperature of the forest ( $T' \approx 300$  K).  $I_S'$  is associated with the radiation of (infrared) light at the temperature  $T'$  as well as predominantly with the air flowing through the forest (as f through the cooling tower of a power plant).

(2) An  $n$  current  $I_n(\text{wood})$  of wood and an  $n$  current  $I_n(\text{O}_2)$  of oxygen. Both  $n$  currents together are connected to the total energy current  $\mu(\text{wood})I_n(\text{wood}) + \mu(\text{O}_2)I_n(\text{O}_2)$ . The factors  $\mu(\text{wood})$  and  $\mu(\text{O}_2)$  are the chemical potentials of wood and gaseous oxygen, respectively, and are mea-

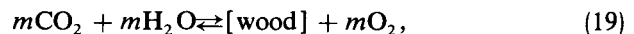
sures of the extent to which the respective  $n$  currents are loaded with energy.

A comparison of Figs. 1 and 2 clearly illustrates the similarity in operation between a heat engine and a forest: just as a heat engine unloads onto a momentum current (or into an angular momentum current or, in connection with a generator, onto a charge current) part of the energy carried into the heat engine by the entropy of an inflowing entropy current, a forest unloads onto several  $n$  currents part of the energy carried into the forest by the entropy of an inflowing entropy current (of light). The fact that the  $n$  currents are loaded with more energy while flowing out of the forest than while flowing into the forest is expressed by the fact that, in the transformation of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  into wood and  $\text{O}_2$ , the values of the associated chemical potentials are increased.

That part of the energy current which is transferred in the forest from the incoming  $S$  current onto the outgoing  $n$  current is given by

$$\begin{aligned} & \mu(\text{wood})I_n(\text{wood}) + \mu(\text{O}_2)I_n(\text{O}_2) \\ & - \mu(\text{CO}_2)I_n(\text{CO}_2) - \mu(\text{H}_2\text{O})I_n(\text{H}_2\text{O}) \\ & = [\mu(\text{wood}) + m\mu(\text{O}_2) - m\mu(\text{CO}_2) \\ & - m\mu(\text{H}_2\text{O})]I_n(\text{wood}) \\ & = \mu I_n(\text{wood}). \end{aligned} \quad (18)$$

Here it has been assumed that one molecule of wood is synthesized from  $m$  molecules of  $\text{CO}_2$  and  $m$  molecules of  $\text{H}_2\text{O}$  while  $m$  molecules of  $\text{O}_2$  are set free in the process. Thus (18) expresses the energetics of the reaction equation



whereby [wood] represents the symbol for one molecule of wood.

The energy current (18) is the "work done" per unit time by the forest. Indeed, (18) expresses an amount of work done per unit time just as, say, the expression  $\Delta\phi I_Q$  expresses the work done per unit time, i.e., the power, of a heat engine plus electric generator. This is evident by considering that, in principle, the energy current (18) can be completely transferred to a charge current  $I_Q$ . This type of transference, namely of energy from an  $n$  current to a  $Q$  current, is just what occurs, for example, in a fuel cell operating reversibly (Fig. 3). Under the assumption of reversibility, the entropy current  $I_S$  flowing into the cell is equal to the entropy current  $I_S'$  flowing out of the cell so that, if both currents flow at the same temperature  $T$ ,  $TI_S - T'I_S' = 0$ . For this reason, the entropy currents and accompany-

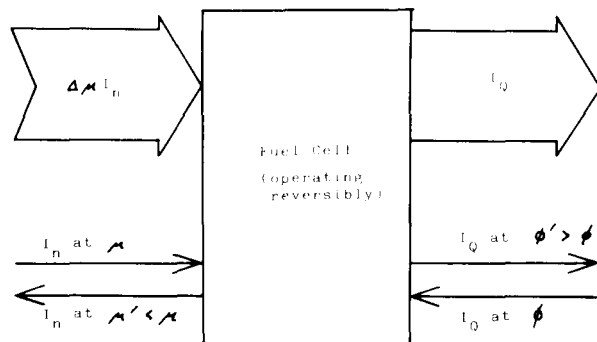


Fig. 3. Energy flow diagram for a fuel cell operating reversibly (see text for explanation of all symbols).

ing energy currents have not been sketched in Fig. 3. For a fuel cell operating irreversibly, the flow of energy  $\Delta\phi I_Q$  out of the machine along with electric charge would differ from the flow of energy  $\Delta\mu I_n$  into the machine along with amount of substance by  $T(I'_S - I_S) = TI_S$  (created), where  $I_S$  (created) expresses the flow of entropy created in the device:

$$\Delta\mu I_n = \Delta\phi I_Q + TI_S(\text{created}). \quad (20)$$

Finally if the horizontal arrows in Fig. 2 are exchanged, left for right, the resulting diagram represents the flow diagram for the reverse process of photosynthesis, namely, for the burning of wood and oxygen to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ .

The example of a forest provides only one simple example of a great diversity of processes which can be described with the help of the quantity  $n$ , its current  $I_n$ , and the "energy load factor"  $\mu$ , i.e., the chemical potential. Nevertheless, this example helps show that the chemical potential  $\mu$ , although traditionally neglected, is at least as useful for understanding many of the processes in the world around us as are the more familiar intensive quantities such as temperature  $T$ , electric potential  $\phi$ , velocity  $\mathbf{v}$ , and angular velocity  $\omega$ .

### VIII. PEDAGOGICAL CONSEQUENCES FOR PHYSICS TEACHING

When emphasizing substance-like quantities, the break-up of physics into sub-branches is nothing more than a classification of natural processes according to the substance-like quantity playing the dominant role in each case. The method of description, however, remains the same from one sub-branch to another as was demonstrated by the above examples. From this point of view then, physics naturally appears as a single set of rules capable of describing the most different processes of nature in a unified way.

Beyond its broad range of application, the description of physical processes with the help of substance-like quantities has the advantage of being easy to grasp. Since the various substance-like quantities can be pictured as different kinds of "stuff," natural processes can be simply visualized in terms of the increasing, decreasing, and flowing of these quantities in space and time. This picture can be presented even without any accompanying mathematical framework. The flow diagrams introduced above provide clear examples of this claim: balancing the amounts of physical quantities associated with the process represented by each diagram is understandable without the explicit help of mathematical formulas. Indeed, these diagrams allow for an elementary graphical calculus which, in an introductory physics course, can be used to get across the idea of how physical processes are described in terms of substance-like quantities. With a little imagination on the part of the teacher, the use of such diagrams can even be incorporated into a kind of domino game.<sup>3</sup>

The Karlsruhe physics project begins with a course<sup>3,4</sup> based upon these ideas for 10- to 12-year-olds (grades 5–6). The central concept of this course is energy, more exactly, the flow of energy and various means of energy transport. By constantly pointing out how the flow of energy plays an important role in the things which happen in our everyday lives, it is brought to the children's attention that energy always requires an "energy carrier" to transport it from one place to another. At first these carriers are quite graspable things which one can see, like food stuffs, fuels, water,

and air. However, as the course progresses, the energy carriers introduced become less and less concrete, finally becoming abstract concepts like electric charge or angular momentum. One advantage of this approach is that physics is no longer broken up into a series of separate branches but, rather, is presented as a general method for describing physical and chemical processes. Accordingly, physics appears as a unified science.

### IX. CONCLUSION

An attempt has been made to present an overview of the fundamental role which substance-like quantities play in physics. An approach to physics based upon these quantities has several advantages over the conceptual structuring of traditional physics:

(1) Since the fundamental quantities of modern physics are substance-like in nature, each such quantity is easy to visualize, namely, as a kind of stuff which is contained in and flows through space and which might even be locally created or destroyed.

(2) A breakup of physics into branches does not upset the unity of the whole since descriptions of the most different physical processes follow the same formal rules. Thus knowledge of a single branch of physics already provides an analogy for the ways and means by which processes are described in other branches as well.

These points are of special relevance to the teaching of physics because this picture can even be introduced at a quite elementary level. It is therefore possible to carry out a course of physics instruction beginning with this simple picture and later incorporating the necessary mathematical support for calculations. In this way, it is possible to present a coherent description of nature which is easy to visualize as well as being in full accord with the most modern principles of physics today.

### ACKNOWLEDGMENT

The author is pleased to acknowledge the generous contributions of his colleagues G. Falk and F. Herrmann to the ideas and form of this article.

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<sup>3</sup>G. B. Schmid, *Phys. Educ.* **17**, 212 (1982).

<sup>4</sup>G. Falk and F. Herrmann, *Neue Physik: Das Energiebuch* (Schroedel-Verlag, Hannover, 1981).

<sup>5</sup>Also called the differential form of the fundamental equation. See, for example, H. B. Callen, *Thermodynamics* (Wiley, New York, 1960), Chap. 2.

<sup>6</sup>F. Herrmann, "Mechanik-Abriss einer Neudarstellung," in *Konzepte eines zeitgemässen Physikunterrichts*, edited by G. Falk and F. Herrmann (Schroedel-Verlag, Hannover, 1979), Vol. 3, p. 80; also, Vol. 5 (1982).

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<sup>9</sup>F. Herrmann and G. B. Schmid, "Rotational dynamics and the flow of angular momentum," In-house report.

<sup>10</sup>G. Falk and F. Herrmann, *Konzepte eines zeitgemässen Physikunterrichts* (Schroedel-Verlag, Hannover, 1981), Chap. 4.