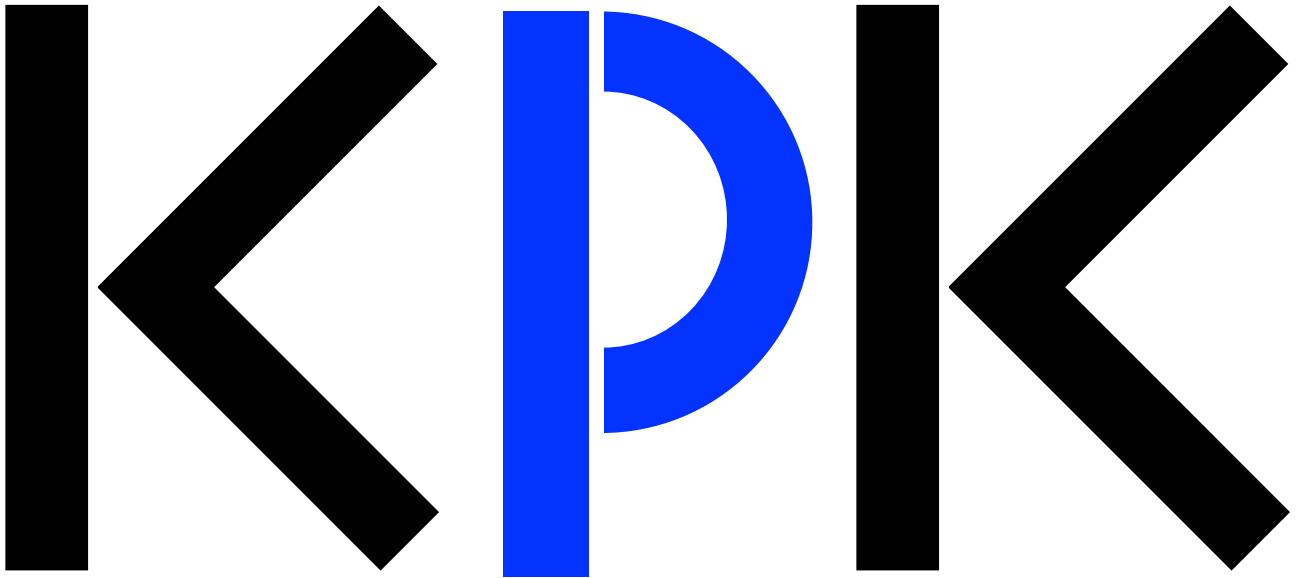


Friedrich Herrmann



The Karlsruhe physics course

Lecture notes

Mechanics

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Lecture notes

- **Mechanics**
- Thermodynamics
- Electromagnetism
- Optics

Der Karlsruher Physikkurs

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1

Substance-like quantities

1. Substance-like quantities

There is a class of physical quantities which are particularly easy to handle: the substance-like quantities. These include:

- mass m
- energy E
- electric charge Q
- momentum \vec{p}
- entropy S
- amount of substance n

and others.

One may imagine each of these quantities as a kind of substance, and one can speak about them as one speaks about a substance. The physical reason for this is that for each such quantity a density (mass density, energy density, charge density ...) and a current (mass flow, energy flow, electric current ...) can be defined.

This fact leads to further properties of the substance-like quantities: They add up when combining two systems into one, Fig. 1.1. If the quantity X has the value X_1 in system S_1 and the value X_2 in system S_2 , it has the value $X_1 + X_2$ in the composed system S . This rule does not apply to non-substance-like quantities, such as temperature, pressure or velocity.

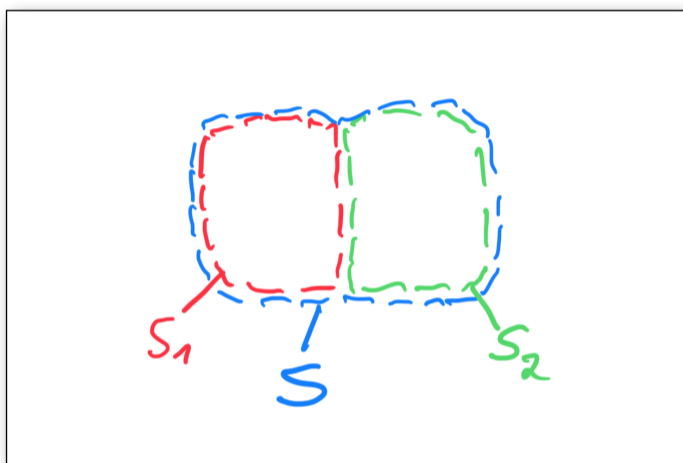


Fig. 1.1

Regarding the additivity of substance-like quantities

The question of whether or not a quantity is conserved is a meaningful question only for substance-like quantities. Energy and electric charge are conserved, entropy and amount of substance are not, because one can create entropy, and can create as well as destroy amount of substance. The question about the conservation of non-substance-like quantities, is meaningless, such as the question: “Is pressure a conserved quantity?”

For historical reasons, the strengths of some currents have their own names: The energy current strength is usually called power, and the momentum current strength is almost exclusively called force. Table 1.1 lists the most important substance-like quantities together with the corresponding currents.

Substance-like quantity		Current strength	
Name	Symbol (unit)	Name	Symbol (unit)
Mass	m (Kilogram, kg)	Mass current	–, (kg/s)
Energy	E (Joule, J)	Power	P (Watt, $W = J/s$)
Electric charge	Q (Coulomb, C)	Electric current	I (Ampere, $A = C/s$)
Momentum	\vec{p} (Huygens, Hy)	Force	\vec{F} (Newton, $N = Hy/s$)
Entropy	S (Carnot, Ct)	Entropy current	–, (Ct/s)
Amount of substance	n (Mol, mol)	Substance current	–, (mol/s)

Table 1.1

Some substance-like quantities and their currents

There are analogies existing between some areas of physics: From a relationship that is valid in one area of physics, one obtains a relationship that is valid in another by purely formal translation. In these analogies, substance-like quantities correspond to each other. In the following text we will often refer to the analogy between mechanics and electricity. In this case, momentum and electric charge, as well as force (= momentum current) and electric current, correspond to each other.

2

Momentum and momentum capacitance

2.1 Definition of momentum

A rolling carriage has momentum. The faster it rolls, and the heavier it is, the more momentum it has. The meaning of what is colloquially called momentum is very much in line with the meaning of the substance-like physical quantity momentum.

Huygens called the momentum “*quantitas motus*”, meaning quantity or amount of movement. A moving body contains a certain amount of momentum, just as an electrically charged body contains a certain amount of electricity.

At first we concentrate on the analysis of one-dimensional, rectilinear movements in the x -direction, and we define:

If a body moves in the positive x -direction, its momentum is positive. If the body moves in the negative x -direction, its momentum is negative. If the body is at rest, its momentum is zero.

Fig. 2.1 shows how the momentum of a body B can be measured. Unit bodies U i.e. bodies each of which carries one (negative) unit of momentum, are allowed to collide with B in such a way that they remain connected to B after the collision (“inelastic collision”). Momentum is thereby transferred from B to the unit bodies. One now lets unit bodies collide with B until B and all unit bodies already attached to it have come to rest. If z unit bodies are required for this, we know that B had z units of momentum at the beginning.

This measuring method assumes that no momentum is lost in the collision and no new momentum is generated. That this is the case can easily be proven in further experiments.

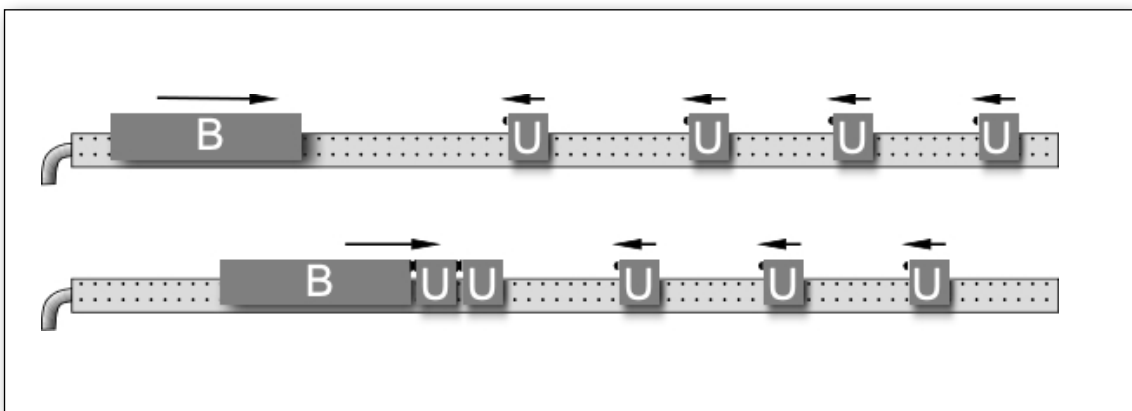


Fig. 2.1

Measuring momentum. B = Body whose momentum is to be measured. U = Body with one unit of momentum.

2.2 Momentum capacitance

We now ask what the momentum of a body depends on and ascertain:

The momentum of a body depends on

- the velocity of the body;
- the mass of the body.

It does not depend on e.g.

- the chemical composition of the body;
- the geometrical shape of the body.

The quantitative investigation shows that for not too high velocities ($v \ll c$) the following applies:

$$p \propto m \cdot v$$

The unit of measurement *Huygens* of the momentum is chosen in such a way that the proportionality becomes an equation:

$$p = m \cdot v \tag{2.1}$$

Of course, this relationship only applies to that class of systems for which it has been experimentally verified: for bodies of not too high velocity. For other systems, e.g. electromagnetic fields, other relationships apply.

Equation (2.1) can also be read as follows: At a given velocity a body contains the more momentum the greater its mass is. Thus the mass is a measure for the *momentum capacity* of a body.

Table 2.1 lists some typical momentum values.

The relation of electricity which is analogous to equation (2.1) is

$$Q = C \cdot U$$

It tells us, that for a given voltage the plates of a capacitor carry the more electric charge Q , the higher the capacity C of the capacitor is.

It is experimentally established that momentum can neither be created nor destroyed:

Momentum is a conserved quantity.

Flying tennis ball	2 Hy
Flying soccer ball	12 Hy
Pedestrian	100 Hy
Moving passenger car	40 000 Hy
Earth (on its orbit around the sun)	$1.8 \cdot 10^{28}$ Hy
Photon of visible light	10^{-27} Hy

Table 2.1

Some typical momentum values

3

Force
