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Writings, 1909–1911

Anna Beck, Translator

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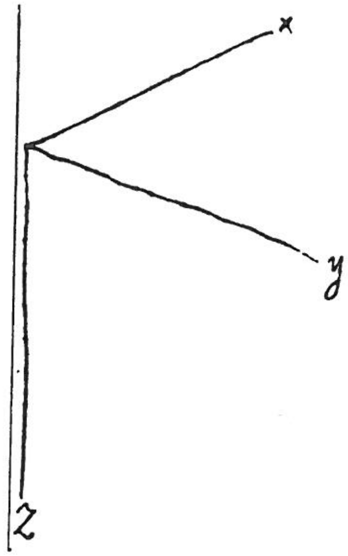
any location at which a cm-measuring rod and water are available. For this reason, this system of measures seems now generally to be used in physics.

The advantage over the other system is only a formal one.



Free Fall

At a place close to the earth's surface we imagine a coord. sys. whose Z-axis is directed vertically upwards. We inquire into the motion of a material point with respect to this system. In order to solve this problem, we must know the magnitude of the force exerted by the earth on the <material> body.

One would expect a priori that this force

1) is proportional to the <mass of the> m. p.
2) depends on the physical quality of the point
3) The force could also depend on the velocity.[14]

<For reasons of symmetry> From the choice of the position of the coordinate system it follows that [p. 14]

$$X = 0 \quad Y = 0$$

Further, one arrives at a correct description of the phenomena if one assumes that gravity does not depend either on the quality or the velocity of the m.p. In this way one obtains

$$\cancel{m}\frac{d^2x}{dt^2} = 0$$

$$\cancel{m}\frac{d^2y}{dt^2} = 0$$

$$\cancel{m}\frac{d^2z}{dt^2} = \cancel{m}g$$

From the two first equations one obtains magnitude. Now we can use the spring to apply forces of specified magnitude to a given mass.

We know that a mat. p. that is not acted upon by external causes moves without acceleration. For it, $\frac{d^2x}{dt^2}$ etc. equal zero. Imagine that the question as to how the acceleration is related to the force for a freely suspended body is investigated with the help of our spring. If we assume that, in the case of some arbitrary, already present motion of the point and an arbitrarily large force,[75] the acceleration is always proportional to the acting force and is directed in the same way, then we obtain

[p. 117]

$$m\frac{d^2x}{dt^2} = X \quad m\frac{d^2y}{dt^2} = Y \quad m\frac{d^2z}{dt^2} = Z$$

<if we assume that the force acts in the direction X>
Because these equations state that
1) acceleration and force have the same direction

$$X : Y : Z = \frac{d^2x}{dt^2} : \frac{d^2y}{dt^2} : \frac{d^2z}{dt^2}$$

2) If m is taken as constant, then the magnitude of the acceleration

$$\sqrt{\left(\frac{d^2x}{dt^2}\right)^2 + \left(\frac{d^2y}{dt^2}\right)^2 + \left(\frac{d^2z}{dt^2}\right)^2}$$

is proportional to the magnitude of the force $\sqrt{X^2 + Y^2 + Z^2}$

If the acting force is not that of our gauge-spring but some other force, then it will be replaced by that force of the gauge-spring that produces the same motion. Then what was said above will hold for arbitrary forces.

particular coordinates always involves the idea of a well-defined experiment concerned with the position of solid bodies.[9]

Let us now make an important remark: In order to define the physical time with respect to a coordinate system, we used *a group of clocks in a state of rest relative to that system.* According to this definition, the time readings or the establishment of the simultaneity of two events have meaning only if the motion of the group of clocks or that of the coordinate system is known.

Consider two nonaccelerated coordinate systems S and S' in uniform translational motion with respect to one another. Suppose that each of these systems is provided with a group of clocks invariably attached to it, and that all clocks belonging to the same system are in phase. Under these conditions, the readings of the group attached to S will define the physical time with respect to S; analogously, the readings of the group attached to S' define the physical time with respect to S'. Each elementary event will have a time coordinate t with respect to S, and a time coordinate t with respect to S'. *But, we have no right to assume* a priori *that the clocks of the two groups can be set in such a manner that the two time coordinates of the elementary event would be the same, or in other words, in such a way that* t *would be equal to* t′. To assume this would mean to introduce an arbitrary hypothesis. This hypothesis has been introduced into kinematics up to the present time.

The second arbitrary hypothesis introduced in kinematics concerns the configuration of a body in motion. Consider a bar AB moving in the direction of its axis with velocity v with respect to a coordinate system S not in accelerated motion. What should we understand by the "length of the bar"? One is at first inclined to believe that this concept does not require any special definition. However, we will immediately see that nothing of the sort is true if we consider the following two methods of determining the length of the rod:

1. One accelerates the motion of an observer furnished with a measuring rod until he attains the velocity v, i.e., until he is at relative rest with respect to the bar. The observer then measures the length AB by successively applying the measuring rod along the bar.

2. Using a group of clocks in phase with each other and at rest with respect to the system S, one determines the two points P_1 and P_2 of S where one finds the two ends of the bar at the instant t; after that, one determines the length of the straight line

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[9] We do not claim that the time and space coordinates must necessarily be defined in such a way that their definitions could serve as the basis of measurement methods that permit the experimental determination of these coordinates—the way it has been done above. But whenever the quantities t, x, y, z are introduced in the capacity of purely mathematical variables, equations in physics will have meaning only if they allow the elimination of these quantities.

that this one inference from mechanics seems to be right, whereas thermal conduction seems not to be amenable to any mechanical interpretation.

Einstein's third comment is a response to a remark by Rutherford on Nernst's lecture. In it Rutherford inquired about the possibility of explaining the decreasing specific heats of solids for lower temperatures by assuming that a "polymerization" takes place within the solid. In a comment preceding Einstein's, Nernst excluded this possibility by arguing that chemical transformations are unlikely to take place at such temperatures. A proposal similar to Rutherford's had been made earlier by Lorentz and discussed by Einstein (see H. A. Lorentz to Einstein, 6 May 1909, and Einstein to H. A. Lorentz, 23 May 1909). In a footnote to the published text of his discussion remark, Einstein added further arguments against Rutherford's proposal: "The specific inductivity would have to approach unity if the temperature decreases to absolute zero. According to this hypothesis, the ultraviolet proper oscillations should not, for ordinary temperatures, exert an influence on the index of refraction or on the specific inductivity." After the Solvay Congress, the polymerization hypothesis was explored by a number of researchers (see, e.g. *Duclaux 1912b* and *Benedicks 1913*), but eventually rejected for reasons such as the ones mentioned by Einstein in his comment (see *Verhandlungen 1914*, p.371)

No. 171 (*Nernst et al. 1914*, p. 239; *Nernst et al. 1912*, pp. 296–297)

10) It is absolutely impossible to explain the decrease of specific heats at low temperatures by assuming rigid bonds between the atoms (reduction in the degrees of freedom). For according to this assumption, solid bodies would have to lose their elastic deformability as they approach absolute zero (the compressibility would have to vanish for $T = 0$), and the infrared proper frequencies would have to become less and less optically discernible, neither of which is true.

The first of the following two comments by Einstein follows a longer explanation by Kamerlingh Onnes, while his second comment responds to a suggestion made by Lindemann; both Kamerlingh Onnes and Lindemannn argued in favor of Rubens's interpretation of the Nernst-Lindemann formula (see the editorial note to Einstein's comment 8 on Nernst's lecture). Kamerlingh Onnes agreed with Rubens that the two frequencies appearing in this formula correspond to two different oscillations of the solid body. But whereas Rubens attempted to identify these oscillations as those of the neutral molecule and the electrically charged atoms, repectively, Kamerlingh Onnes argued that in a molecular system longitudinal and transverse oscillations exist which could have diffeent frequencies because of the way in which spatially extended atoms interact via parts of their surfaces. Lindemann, on the other hand, attempted to explain the existence of two different frequencies by assuming the interatomic forces to be directed so that, for example, oscillations along the diagonal and oscillations along one of the sides of a cubic lattice would have different frequencies. For a modern discussion of the role of the modes of oscillation of a lattice, see, e.g., *Born and Huang 1954*.

No. 177 (*Nernst et al. 1914*, p. 241; *Nernst et al. 1912*, p. 291)

11) The formula of Nernst and Lindemann undoubtedly represents a significant step forward. But we should beware, in my opinion, of seeing in it more than an empirical formula. It was clear a priori that atoms of solid bodies cannot behave thermodynamically exactly like infinitely weakly damped radiation resonators; in my opinion, the incompletely monochromatic character of atomic oscillations is the reason why experience deviates

from theory. A more careful investigation must show whether this conception will hold up.

The following discussion remark is transcribed from *Nernst et al. 1914*, p. 241. See also *Nernst et al. 1912*, p. 300. A manuscript version does not exist.

If the forces that cause the oscillations are proportional to the distance from the equilibrium position, then it follows from the symmetry of the cubic system that a material point cannot possess two frequencies, at least not as long as one adheres to the laws of mechanics.

In a comment following Einstein's previous remark, Poincaré brought the subject of the behavior of gases at low temperatures into the discussion. In the course of the ensuing exchange among Nernst, Poincaré, Rutherford, Kamerlingh Onnes, Einstein and Langevin, Nernst related this behavior to the rotational motion of the molecules and mentioned the difficulties of applying the "quantum theory" to this motion. In his Solvay lecture, Einstein criticized Nernst's theoretical treatment of the rotational motion of molecules, and made a remark similar to the comment printed below; see *Einstein 1914* (Doc. 26), pp. 350–351.

No. 181 (*Nernst et al. 1914*, p. 242; *Nernst et al. 1912*, p. 301)

12) The optical <and energetical> investigation of the optical properties of gases with a diatomic molecule with an electric moment is in fact of the greatest importance, because from the relation between the coefficient of emission and the frequency (or the temperature, if the frequency is given) one can obtain directly (using electrodynamics, to be sure) the statistical law of rotational motion.

In §6 of his lecture, Nernst claimed that his heat theorem (the third law of thermodynamics) can be derived from the quantum theory of specific heats. This claim gave rise to an extended controversy between Einstein and Nernst on the status of the heat theorem, starting with the discussion remark printed below. The conflict resurfaced during the second Solvay conference where it led to a lengthy discussion following *Grüneisen 1921* (see *Grüneisen et al. 1921*, pp. 290–301).

No. 186 (*Nernst et al 1914*, p. 243; *Nernst et al. 1912*, p. 302)

13) I would like to remark here that, as far as I can see, Nernst's heat theorem cannot be inferred from the vanishing of the specific heat in the vicinity of absolute zero, even though its validity is made much more plausible by this. For the question is whether, in a sufficiently close proximity to abs. zero, a system can be brought reversibly & isothermally from a state A to a state B *without the addition of heat*. This could not be inferred from the weakness of the molecular agitation if the transition from A to B could only be produced by using this minimal residue of thermal agitation; in that case it would be absolutely impossible to transfer the system from state A to state B at absolute zero. Nernst's theorem amounts to the assumption (that is quite plausible, to