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Herman Erlichson

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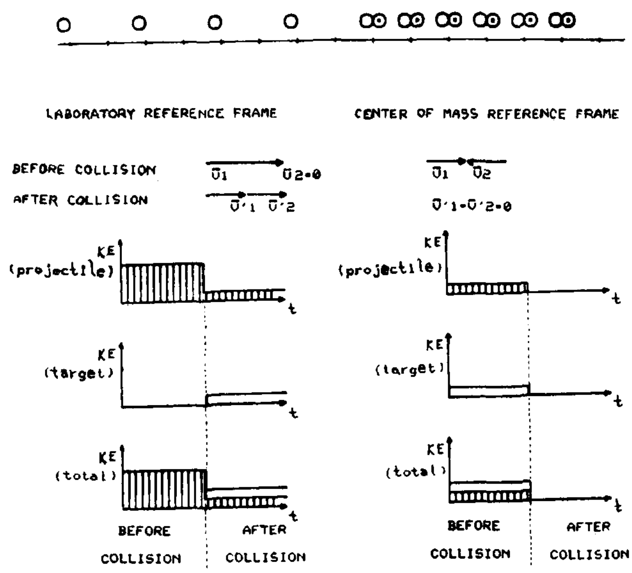

Fig. 10. Perfectly inelastic one-dimensional collision. Simulation and graphs of the velocities and the kinetic energies in the laboratory and the center-of-mass frame of reference.

IV. NOTES ABOUT DIDACTICAL APPLICATIONS

The package presented above has been used by first-year undergraduate students of physics and engineering at the University of Pavia. The students worked in groups of two and had three sessions at the terminal, one for each part of the package.

As only one-dimensional collisions are considered in detail by lecturers, two-dimensional collisions were "discovered" by the students while working with the package. By applying the theory to many simulated collisions of this type they were able to carry out a quantitative analysis that would have been otherwise impossible.

Students were given a guide which consisted of instructions for using the terminal and for running programs. They also received notes highlighting the major points of the program and had to return a questionnaire with their comments and suggestions about the package and the use of the computer. Students usually enjoy using a computer and their performances improve substantially from session to session.

The computer, as a support to traditional teaching, provides an effective means of enhancing the interest in and the understanding of the topics presented in elementary undergraduate lectures in physics. Computers should not be perceived as a threat to physical intuition as long as it is ensured that they bridge effectively between the conceptual world of theory and the one of everyday experience.

The listing of the program is available on request from the authors.

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Internal energy in the first law of thermodynamics

Herman Erlichson
Department of Applied Sciences, The College of Staten Island, Staten Island, New York 10301

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The definition of the internal energy of a thermodynamic system in most introductory texts usually states or implies that the c.m. kinetic energy of the system is not part of the internal energy. This is inconsistent with their statement of the first law of thermodynamics as $\Delta U = Q - W$. If the c.m. kinetic energy is not considered part of U, the first law should be stated as $\Delta U + \Delta K_{\text{c.m.}} = Q - W$. Several examples are given. Clarification of this point is needed in many widely used texts.

I. INTRODUCTION

For some time I have pondered the meaning of internal energy in the first law of thermodynamics. A widely used introductory text tells us, "Internal energy can be interpreted in terms of microscopic mechanical energy, that is, kinetic and potential energies of individual molecules in a material."[1] This leads one to believe that internal energy does not include the gross c.m. kinetic energy of the assembly of molecules. This certainly seems reasonable and consistent with the use of the adjective "internal." Another well-known text states, "The temperature of a gas is related to the total translational kinetic energy measured with respect to the center of mass of the gas. The kinetic energy associated with the motion of the center of mass of the gas has no bearing on the gas temperature."[2] Since we know that the internal energy is a function of the thermodynamic coordinates, this confirms our notion that the c.m. kinetic energy is not part of the internal energy. A third text explicitly states, "we shall define the internal energy of a system as the sum of its internal kinetic and potential energies"[3] (with internal kinetic energy as the kinetic energy relative to the c.m.).

The purpose of this paper is to show that this widely accepted meaning of the internal energy is inconsistent with the widely used statement of the first law as $\Delta U = Q - W$. We will show that if U has the commonly accepted meaning then the correct statement of the first law is $\Delta U + \Delta K_{\text{c.m.}} = Q - W$. We offer several examples to further stress our point and we hope that future texts will correct this common error.

II. THE FIRST LAW OF THERMODYNAMICS

If we have a system of particles (a thermodynamic system) undergoing a process, the work of all the forces equals the change in kinetic energy of all the particles,

$$W = \Delta K. \tag{1}$$

W is the sum of the work of external forces, W_{ext}, and the work of internal forces W_{int}. K is the sum of c.m. kinetic energy $K_{\text{c.m.}}$, and "internal" kinetic energy K_{int}. Thus

$$W_{\text{ext}} + W_{\text{int}} = \Delta K_{\text{c.m.}} + \Delta K_{\text{int}}. \tag{2}$$

The work of the external forces is the sum of the work of the external macroscopic forces $W_{\underset{\text{macro}}{\text{ext}}}$, and the work of the external microscopic forces $W_{\underset{\text{micro}}{\text{ext}}}$. The work of the external microscopic forces is what we commonly call the heat Q. Hence,

$$W_{\text{ext}} = W_{\underset{\text{macro}}{\text{ext}}} + W_{\underset{\text{micro}}{\text{ext}}} = W_{\underset{\text{macro}}{\text{ext}}} + Q. \tag{3}$$

Furthermore, the work of the external macroscopic forces, $W_{\underset{\text{macro}}{\text{ext}}}$, is usually denoted by the simple symbol $-W$, where W is the work of the system against the external macroscopic forces; so

$$W_{\text{ext}} = -W + Q. \tag{4}$$

Substituting Eq. (4) into Eq. (2) we have

$$Q - W + W_{\text{int}} = \Delta K_{\text{c.m.}} + \Delta K_{\text{int}}. \tag{5}$$

We bring W_{int} to the other side of the equation and identify $\Delta K_{\text{int}} - W_{\text{int}}$ as the change in the internal energy ΔU:

$$\Delta K_{\text{int}} - W_{\text{int}} = \Delta U. \tag{6}$$

Equation (5) thus becomes

$$\Delta U + \Delta K_{\text{c.m.}} = Q - W. \tag{7}$$

Equation (7) is inconsistent with the common textbook statement of the first law,

$$\Delta U = Q - W, \tag{8}$$

unless the U of Eq. (8) includes $K_{\text{c.m.}}$. We have earlier shown that the widely accepted meaning of U in introductory texts is that it does not include $K_{\text{c.m.}}$. We conclude that the first law statement in these texts is incorrect, or at least inconsistent with their definition of the internal energy U.

III. ILLUSTRATIONS OF THE INCONSISTENCY

We offer several examples of the inconsistency we have noted. The first two examples are drawn from two of the texts referred to earlier.

Example 1. Halliday and Resnick[4] query, "An iron ball is dropped onto a concrete floor from a height of 10 m. On the first rebound it rises to a height of 0.50 m. Assume that all the macroscopic mechanical energy lost in the collision with the floor goes into the ball. The specific heat of iron is 0.12 cal/g °C. During the collision (a) Has heat been added to the ball? (b) Has work been done on it? (c) Has its internal energy changed? If so, by how much? (d) How much has the temperature of the ball risen after the first collision?"

This problem is conveniently analyzed in terms of two macroscopic systems, the ball and the floor. In this model any heat exchanges which occur *inside* the ball between the ball interaction volume adjacent to the floor and the rest of the ball will not show up in the Q which the ball exchanges with the floor. Let us assume a rigid floor and no permanent deformation of the ball. If we now consider the ball over the interaction interval we note that $W = 0$ since neither the gravitational force or the floor contact force does net work during the collision interval (the floor contact force does not move and the gravitational force has no net displacement over the collision interval). The author further tells the student to assume that no energy is transferred to the floor, so $Q = 0$ for the floor and also for the ball. Hence, if the student applies Eq. (8) to the ball over the collision interval he would find $\Delta U = 0$. This is clearly incorrect since the temperature of the ball rises as a result of the collision. The authors partially protect themselves against an incorrect application of Eq. (8) by their statement, "Assume that all the macroscopic mechanical energy lost in the collision with the floor goes into the ball," but the fact remains that the student cannot correctly solve this problem by using Eq. (8). He must use Eq. (7). If he does so, he correctly finds $\Delta U = -\Delta K_{\text{c.m.}} = mc\Delta T$.

In the more realistic case that both the ball and the floor get warmer, assume Q enters the floor. Since we continue to assume a rigid floor, the increase in internal energy of the floor would be $\Delta U_f = Q$. If we now apply the first law to the ball we find $\Delta U_b + \Delta K_{\text{c.m.}} = -Q$, or $\Delta U_b = -\Delta K_{\text{c.m.}} - Q$. If we sum the increases in internal energies of the floor and the ball we find, as we expect, $\Delta U_f + \Delta U_b = -\Delta K_{\text{c.m.}}$ In a similar manner, the assumption of a rigid floor and a ball which returns to its original shape can be removed. Since the macroscopic work of the ball on the floor is the negative of the macroscopic work of the floor on the ball we would once again find $\Delta U_f + \Delta U_b = -\Delta K_{\text{c.m.}}$

Example 2. Sears *et al.*[5] query, "What must be the initial velocity of a lead bullet at a temperature of 25 °C, so that the heat developed when it is brought to rest shall be just sufficient to melt it?"

Let us assume that the bullet embeds itself into a wall. If we apply Eq. (8) to the collision process, with the bullet as the system, we find

$$\Delta U = Q - W, \tag{9}$$

where W is the work of the system against the resisting force of the wall. Now, if the wall has no change in internal energy, an application of Eq. (8) to the wall as the system yields $0 = Q_{\text{wall}} - (-Fd)$, where F is the resisting force and d is the penetration distance. Since the Q of the bullet is the negative of Q_{wall}, we have $Q = Fd$. Putting this value of Q into Eq. (9), and noting that $W = Fd$, we find

$$\Delta U = Fd - Fd = 0, \tag{10}$$

which is clearly wrong.

The way out of this dilemma is to use the correct Eq. (7) for this problem. If we apply Eq. (7) to the bullet we have

$$\Delta U + \Delta K_{\text{c.m.}} = Q - Fd = Fd - Fd = 0, \tag{11}$$

$$\Delta U = -\Delta K_{\text{c.m.}}. \tag{12}$$

Since $\Delta K_{\text{c.m.}} = -Fd = -Q$, we also have $\Delta U = Q$. Thus, Eq. (7) leads to the correct result.

Example 3. We offer as a final example the case of a block sliding to rest on a rough table.

If we apply Eq. (8) to this problem and assume no change in the energy of the surface we have, for the block,

$$\Delta U = Q - W = Q - f_k s, \tag{13}$$

where f_k is the kinetic frictional force and s is the stopping distance.[6] An application of Eq. (8) to the surface yields

$$0 = -Q - (-f_k s), \tag{14}$$

or $Q = f_k s$. If we put this value of Q into Eq. (13) we find $\Delta U = 0$, which we know is wrong.

If we apply the correct Eq. (7) to the block we have

$$\Delta U + \Delta K_{\text{c.m.}} = Q - W = f_k s - f_k s = 0,$$

$$\Delta U = -\Delta K_{\text{c.m.}} = \tfrac{1}{2} M V_i^2, \tag{15}$$

the correct result.

IV. CONCLUSION

We see from the foregoing examples that our introductory physics books should either (a) present Eq. (7) as the proper statement of the first law of thermodynamics, or (b) keep Eq. (8) but state explicitly that the internal energy U includes the c.m. kinetic energy of the system.

We note in passing that although it is hard to find a physics text which uses Eq. (7), it is not so hard to find an engineering thermodynamics book which does so. The text by Sonntag and Van Wylen[7] uses

$$\delta Q = dU + d(KE) + d(PE) + \delta W, \tag{16}$$

which is the same as our Eq. (7) except that the work of the gravitational force has been separated from that of the other external forces.

[1] F. W. Sears, M. W. Zemansky, and H. D. Young, *University Physics* (Addison-Wesley, Reading, MA, 1982), 6th ed., p. 350.

[2] D. Halliday and R. Resnick, *Fundamentals of Physics* (Wiley, New York, 1981), 2nd. ed., p. 380.

[3] M. Alonso and E. J. Finn, *Fundamental University Physics* (Addison-Wesley, Reading, MA, 1967), p. 250.

[4] Reference 2, Problem 37, p. 373.

[5] Reference 1, Problem 18-6, p. 361.

[6] The work of a constant force **F** is **F·s**, where **s** is the displacement of the particle on which the force acts (equivalent to the displacement of the point of application of the force). In the case of the force $\mathbf{f}_k$ exerted by the block on the surface, this force acts on a sequence of particles in the surface. As a convenience, one can picture $\mathbf{f}_k$ as acting first on one particle, giving it a small displacement, then passing on to the next particle, giving it a small displacement, etc. The sum of all the works of $\mathbf{f}_k$ on all the particles is equal to f_k multiplied by the total displacement of the force (equal to the total displacement of all the individual particles on which $\mathbf{f}_k$ acts). Of couse, after $\mathbf{f}_k$ acts on a particular particle that particle is acted on by the neighboring particles and is restored to its original position but this restoring phase does not enter into the work of $\mathbf{f}_k$. The total result is that the work of $\mathbf{f}_k$ is $f_k s$ even though the overall surface has not moved.

[7] R. E. Sonntag and G. J. Van Wylen, *Introduction to Thermodynamics: Classical and Statistical* (Wiley, New York, 1971).

Experiment to verify the second law of thermodynamics using a thermoelectric device

V. K. Gupta,[a] Gauri Shanker,[b] B. Saraf,[c] and N. K. Sharma

Centre for Development of Physics Education, University of Rajasthan, Jaipur 302004, India

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An experiment to verify the second law of thermodynamics using a thermoelectric device is described. The response of the device when it is used as a Seeback-effect heat engine after filtering out the contributions of the associated irreversible parts is studied as a function of the temperatures of the hot and cold junctions. Likewise its response as a Peltier-effect heat pump is also investigated. The experimental results are in close agreement with the predictions of the second law of thermodynamics.

I. INTRODUCTION

The second law of thermodynamics[1] makes a negative statement in the sense that it tells what is not permissible in nature. A positive and quantitative statement that may be inferred from it is in the form of the response of a reversible heat engine or heat pump as a function of the temperatures of the source and sink.