What is a reversible process?
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I. INTRODUCTION

The way thermodynamics concepts are presented in introductory physics courses creates much confusion and leaves students befuddled. The mysterious nature of heat is responsible for much of the vagueness of thermodynamics as it is presented to students. Nowhere is the lack of clarity more apparent than in the treatment of reversible processes. Just to illustrate the problem, I quote here the definition of a reversible process from Resnick, Halliday, and Krane.1

In a reversible process, we make a small change in a system and its environment; by reversing that change, the system and its environment will return to their original conditions.

The definitions in other introductory books are not much different or clearer.2,3 Even an intermediate-level book by Zemansky and Dittman has a very similar definition.4

A reversible process is one that is performed in such a way that, at the conclusion of the process, both the system and the local surroundings may be restored to their initial states, without producing any changes in the rest of the universe.

The trouble with these definitions is that it is not clear what returning to the original conditions means. Many students take it to mean that the system and the environment return to the energy states that are the same as before when the process is carried out in the reverse direction. It most certainly does not mean that, because no matter how a process is conducted, the total energy of the system and the environment is conserved.5 Therefore, when the system returns to its initial energy state, the environment must also do so, whether the process is reversible or not. The reversibility of a process has nothing to do with energy conservation.

The key to the idea of reversibility lies in the second law of thermodynamics which forbids any real process from being reversible. Therefore, we should discuss the second law of thermodynamics before or along with the definition of a reversible process. It is a mistake to introduce the idea of reversibility well before the second law has been discussed. In the following, I suggest that a more appropriate pedagogical approach would be to introduce students to the concept of a quasi-static process first and then make use of the Carnot cycle to develop the concept of reversibility.

II. QUASI-STATIC PROCESSES

A quasi-static process is a change in the state of a system that is conducted infinitesimally slowly such that, at each instant, the system is in thermodynamic equilibrium with its environment, and its thermodynamic properties, such as volume, pressure, and temperature, remain well-defined throughout the process. Quasi-static processes are often misunderstood to be reversible, especially in elementary physics texts. Because quasi-static processes only deal with a particular forward process without regard to the reverse process, they may or may not be reversible in the sense described in the following. There are processes, such as the expansion of a gas fitted with a piston, subject to sliding friction that are quasi-static but not reversible.6

III. REVERSIBLE PROCESSES

A direct way to address the question of reversibility is to introduce the second law of thermodynamics as given by Clausius’s inequality about the heat absorbed divided by the absolute temperature at which it is absorbed,7

\[ \oint \frac{\Delta Q}{T} \leq 0, \quad (1) \]

where, if the equality holds, the process is reversible. Although this approach to the second law of thermodynamics has an advantage of being direct and, therefore, successful in avoiding the unnecessary language, it is too abstract for an introductory course. In this respect the traditional statements of Kelvin-Planck8 and Clausius9 have advantages, because they relate more closely to common experience about nature and, hence, are more suitable for an introduction to thermodynamics. However, even in the traditional approach, a correct definition of a reversible process must make use of Eq. (1) because it states the necessary requirement of all reversible processes. Therefore, the challenge for introductory physics courses is to find a physically reasonable pedagogical path from the Kelvin-Planck and Clausius statements of the second law to Eq. (1).

I have found that the Carnot cycle provides a good path to get to the reversibility of a process without running into seemingly ad hoc steps, similar to the approach suggested by Tobin.10 To be specific, recall that in a Carnot cycle an ideal gas undergoes four steps quasi-statically, two of which are isothermal and the other two adiabatic.11 Although the steps in the Carnot cycle are reversible, we do not need their reversibility at this stage. Without using the reversibility of the
processes, and just relying on their quasi-static nature, a student can discover the following two important conclusions about a Carnot cycle by elementary calculations:

1. The sum of the quantity \( \Delta Q/T \) for the system over an entire cycle is zero, where \( \Delta Q \) is the heat exchanged with the environment at temperature \( T \).
2. In each of the four steps of the Carnot cycle, the quantity \( \Delta Q/T \) is the same for the system as for the environment, but with the opposite sign.

A reversible process can then be defined by a generalization of the observations made for a Carnot cycle, and their extension to all quasi-static processes in which \( |\Delta Q/T| \) for every infinitesimal step is the same for the environment and the system.

\[
\frac{\Delta Q}{T} \bigg|_{\text{system}} = \frac{\Delta Q}{T} \bigg|_{\text{environment}}, \tag{2}
\]

then the process is reversible. An irreversible process is a process where Eq. (2) does not hold, that is,

\[
\frac{\Delta Q}{T} \bigg|_{\text{system}} \neq \frac{\Delta Q}{T} \bigg|_{\text{environment}}. \tag{3}
\]

IV. REVERSIBLE PROCESSES AND ENTROPY

The definition of a reversible process based on \( \Delta Q/T \) of the system and the environment does not address the physical meaning of returning to the original conditions when the process is carried out in the opposite direction. To find the physical meaning of the reversibility of a process, it is necessary to examine the conclusion about the vanishing of \( \Delta Q/T \) of the system in a Carnot cycle irrespective of the amount of the working substance and the placement of the cycle in \((P, V, T)\) space, and help students realize that there must exist a state property, \( S \), called entropy.\(^7\) The change in entropy of a system during a reversible process is defined as

\[
\Delta S = \int \left( \frac{\Delta Q}{T} \right)_{\text{reversible}}. \tag{4}
\]

In terms of entropy, the second law of thermodynamics for all processes in nature is stated succinctly as usual,

\[
\Delta S_{\text{net}} = \int \left( \frac{\Delta Q}{T} \right)_{\text{system}} + \int \left( \frac{\Delta Q}{T} \right)_{\text{environment}}, \tag{5}
\]

where the equality holds only for a reversible process. It is important to stress that the inequality in Eq. (5) states that the entropy changes in an irreversible process cannot be given by the sum \( \Sigma \Delta Q/T \).

By using the definition of entropy, we can compactly state the necessary requirements of a reversible process as given by Landau and Lifshitz.\(^12\)

“Reversible processes are those in which the entropy of the closed system remains constant, and which can therefore take place in the reverse direction. A strictly reversible process is, of course, an ideal limiting case; processes actually occurring in Nature can be reversible only to within a certain degree of approximation.”

Hence, reversible processes are idealized processes in which entropy is exchanged between a system and its environment and no net entropy is generated.\(^13\) Therefore, a cyclic process of a system that generates a net entropy change is not reversible because it would leave the environment in a state of different entropy although the energy of the environment will not have changed. We can now give a definitive meaning to reversing a reversible process: Reversing a reversible process brings both the system and the environment back to the original entropy states.

Although not all quasi-static processes are reversible, the converse statement that all reversible processes are quasi-static is true. For example, the effusion of gas molecules from a tiny hole in a balloon can be very slow so that at each instant the balloon has well-defined values of mass, pressure, temperature, and volume, and yet the net entropy of the system plus the environment increases. Thus, a quasi-static process does not necessarily have to be reversible. On the other hand, entropy is not conserved in any process that involves discontinuities. Hence, a reversible process must be conducted quasi-statically.

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\(^3\)H. Young and R. Freedman, Sears and Zemansky’s University Physics (Addison-Wesley, New York, 2004), 11th ed., p. 755.


\(^6\)The irrelevance of energy conservation for the definition of a reversible process also holds true of other conserved quantities, as is clear in the abstract formulation of thermodynamics expounded by H. Callen in Thermodynamics and an Introduction to Thermostatistics (Wiley, New York, 1960), p. 63.


\(^8\)Rudolf Clausius, “Ueber die bewegende Kraft der Wärme,” Ann. Phys. Chem. 79, 368–397 (1850); 79, 500–524 (1850); English translation in Philos. Mag. 2, 1–21 (1851); 2, 102–119 (1851).


\(^10\)Note that the term adiabatic is used with different meanings in different parts of physics. In the Carnot cycle, adiabatic implies the absence of heat exchange with the environment.
