

Thermodynamics
À la Manière de TASAKI

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Chapter 0

Introduction

This note provides a short introduction to thermodynamics, the classical macroscopic theory governing the interconversion of heat and work. Following the treatment in [Tas01], we develop the subject through an axiomatic approach. The guiding postulates are summarized as follows:

- Definition 1.3.3
A thermodynamic system in thermal equilibrium is characterized by a single intensive parameter – the “temperature” – together with a finite set of extensive parameters.
- Definition 2.1.2 – Joule’s Experiment
There is at least one adiabatic process in which the extensive parameters of a state remain constants while the “temperature” increases. During this “temperature” increasing process, positive work is done on the system.
- Definition 2.1.3 – The First Law of Thermodynamics
The work done by a thermodynamic system during an adiabatic process depends solely on the initial and final states.
- Definition 2.2.2 – Planck’s Statement
The temperature-increasing adiabatic process described in Joule’s experiment is irreversible.
- Definition 3.0.2
Thermal interactions between systems behave regularly in the thermodynamic limit.
- Definition 4.1.1 – Adiabatic Expansion
For any given state, there exists a lower “temperature” state that is accessible via an adiabatic process.

Throughout the presentation, we assume familiarity with basic mathematics and classical mechanics, particularly Newtonian mechanics.

Chapter 1

Equilibrium States

1.1 Thermodynamics – Overview

Thermodynamics is a branch of classical, macroscopic physics. A typical system – say, a tablespoon of water – contains approximately Avogadro’s number $\sim 10^{23}$ of molecules, making it impossible to track their motions by solving such an enormous number of equations of motion. Instead, macroscopic observations and experiments rely on statistical averages; remarkably, only a small number of parameters survive, and these determine the macroscopic state of a substance.

We (temporarily) restrict our attention to simple systems, defined as systems that are macroscopically homogeneous, isotropic, and unchanged, that are large enough so that surface effects can be neglected, and that are not acted on by electric, magnetic, or gravitational fields [Cal60].

We consider physical systems under special conditions – equilibrium states.

1.2 Extensive Parameters

In brief, a thermodynamic system is a black box equipped with mechanically accessible channels: through these mechanical handles, we can measure work, energy, and other mechanical quantities that reveal both mechanical and non-mechanical properties of the system.

Consider a single kind, i.e., a single-component substance, as a simple thermodynamic system. Such a system, say X , may have different states, but our interest here is restricted to equilibrium states, in which all macroscopic properties remain unchanged in time. A finite set of parameters fully characterizes any thermally equilibrium state of the system.

Definition 1.2.1 (Extensive Parameters). Let X be a thermodynamic system. We assume that its equilibrium state is fully determined by specifying a finite

set of non-negative parameters,

$$\begin{pmatrix} X^1 \\ \vdots \\ X^n \end{pmatrix} \in \mathbb{R}_{\geq 0}^n, \quad (1.1)$$

such that for any scalar $\lambda > 0$:

$$\lambda \begin{pmatrix} X^1 \\ \vdots \\ X^n \end{pmatrix} = \begin{pmatrix} \lambda X^1 \\ \vdots \\ \lambda X^n \end{pmatrix}, \quad (1.2)$$

where $\mathbb{R}_{\geq 0}$ stands for the set of non-negative real numbers. Parameters satisfying this homogeneity property – that is, quantities that scale linearly with the size of the system – are called extensive parameters.

Example 1.2.1 (Fluids). Consider a fixed volume, say a container full of fluid with volume V , and let m be its mass. The following parameters represent its macroscopic state, $\begin{pmatrix} V \\ m \end{pmatrix}$. Consider the case $\lambda = 2$. The left-hand side, $2 \begin{pmatrix} V \\ m \end{pmatrix}$, represents the operation of taking two identical containers of the same fluid and regarding them as a single system. The right-hand side, $\begin{pmatrix} 2V \\ 2m \end{pmatrix}$, is a system with twice the volumes and twice the mass. The homogeneity assumption states that these two systems are identified – they represent the same macroscopic state, $2 \begin{pmatrix} V \\ m \end{pmatrix} = \begin{pmatrix} 2V \\ 2m \end{pmatrix}$.

Remark 1 (Amount of Substance). For a single-component system of substance, say X , we define the amount $n(X)$ of substance by

$$n(X) := \frac{m}{M(X)}, \quad (1.3)$$

where $M(X)$ is an arbitrary constant associated with the substance. As one easily verifies, $n(X)$ is also an extensive parameter. Since $M(X)$ is arbitrary, several choices are possible:

- $M(X) = 1$

In this case, the amount of substance coincides with its mass.

- $M(X)$ is the “atomic weight” of X

Relative to ^{12}C , the relative atomic mass of X is given by:

$$A_r(X) := \frac{m(X)}{m(^{12}\text{C})/12}. \quad (1.4)$$

See Atomic Weights and Isotopic Compositions - Column Descriptions.¹

¹<https://www.nist.gov/pml/atomic-weights-and-isotopic-compositions-column-descriptions>

By consulting a table of Standard Atomic Weights² or via some classical gravimetric analysis, one may choose an appropriate value for $M(X)$.

For a multicomponent system, $X = \{X^i \mid i \in I\}$ of some index I , assuming the chemical composition does not change, we may define

$$n(X^i) := \frac{m_i}{M(X^i)}, i \in I, \quad (1.5)$$

and the total amount of substance $n(X)$ is given by their sum, $n(X) = \sum_{i \in I} n(X^i)$.

Thus, given a table of atomic masses, we can determine the empirical formula for a multicomponent system X . For example, the following substances both have the empirical formula CH :

- acetylene (C_2H_2)
- benzene (C_6H_6)

If the Boyle-Charles law provides a good approximation, i.e., when the “temperature” is sufficiently high and the density is sufficiently low, then for any gas we may determine the following ratio:

$$R := \frac{pV}{mT}, \quad (1.6)$$

where p is the pressure, V the volume, m the mass, and T absolute “temperature” to be introduced later in Definition 4.2.1. Experimentally, one finds

$$R_{\text{acetylene}} \approx 3R_{\text{benzene}}. \quad (1.7)$$

Thus, if we choose $M_{\text{acetylene}}$ and M_{benzene} such that $\frac{M_{\text{acetylene}}}{M_{\text{benzene}}} \approx 3$, then we obtain the following approximate relation

$$\frac{pV}{nT} = \text{constant}, \quad (1.8)$$

for both acetylene and benzene. Hence, if we select the empirical formula acetylene = $C_k H_l$, for some integers k and l , then benzene = $C_{3k} H_{3l}$. Such a relation is an example of an equation of state; see Example 3.3.1.

Exercise 1.2.1. Find the definition, numerical value, and unit of the molar gas constant R from CODATA.³

We now use the amount of substance, N , as an extensive parameter of a system, so its macroscopic state is represented as $\begin{pmatrix} V \\ N \end{pmatrix}$.

Definition 1.2.2 (Juxtaposition). By juxtaposition, we mean placing two systems side by side without any mechanical or chemical interaction. The resulting

²<https://www.nist.gov/pml/periodic-table-elements>

³<https://physics.nist.gov/cuu/Constants/>

object is itself another thermodynamic system. Let X and Y be two systems, and define their juxtaposition by

$$X \oplus Y = \begin{pmatrix} X^1 \\ \vdots \\ X^n \end{pmatrix} \oplus \begin{pmatrix} Y^1 \\ \vdots \\ Y^m \end{pmatrix} \quad (1.9)$$

or equivalently $X \oplus Y = \begin{pmatrix} X \\ Y \end{pmatrix}$. Note that these two systems may, in general, have different numbers of extensive parameters; that is, n and m need not coincide. Since $X \oplus Y$ is another thermodynamic system, it must satisfy the homogeneity property:

$$\lambda(X \oplus Y) = (\lambda X) \oplus (\lambda Y), \lambda > 0. \quad (1.10)$$

Remark 2 (Metaprinciple of Thermodynamics). Anything that thermodynamics does not *explicitly* prohibit can occur in reality.

In thermodynamics what is not forbidden by its principles may happen. [Oon]

We should consider this, as an empirical fact, a metaprinciple of thermodynamics. This metaprinciple of thermodynamics does not, of course, imply any meaningful propositions about statements that are meaningless in thermodynamics or that the principles do not directly mention. For a juxtaposition $X \oplus Y$, for instance, they do not interact chemically or mechanically but they can “thermally” interact.

1.3 Walls

Some extensive parameters of a system have mechanical accesses. A typical example is the volume of a gas contained in a cylinder with a movable piston.

Definition 1.3.1 (Walls – Insertion and Removal). Let $0 < \lambda < 1$. Consider the following operation:

$$X \mapsto \lambda X \oplus (1 - \lambda)X. \quad (1.11)$$

Experimentally, this operation can be realized by inserting a thin, impermeable wall that prevents the passage of substances. For an equilibrium state of a system, we assume that both the insertion and the removal of such a wall can be performed with no mechanical work.

Example 1.3.1. Let X be a system in Example 1.2.1, specified by $\begin{pmatrix} V \\ N \end{pmatrix}$. Suppose we insert a thin wall in order to slice the system into two subsystems. During this wall insertion process, only the edge of the wall is exposed to the pressure due to the fluid. This edge has a length of order L , and the wall

must be pushed a distance of the same order L . Hence, the mechanical work W required scales as $W \in \Theta(L^2)$. Given any permissible error $\epsilon > 0$, we may choose a sufficiently large $L > 0$ such that $|\frac{W}{V}| < \epsilon$. Indeed, the ratio $|\frac{W}{V}|$ scales as $\frac{1}{L}$, so $\frac{W}{V} \rightarrow 0$ as $L \rightarrow +\infty$. Hence, in the thermodynamic limit $L \rightarrow +\infty$, we may idealize that the thin wall insertion requires no work for an equilibrium state of the system.

Remark 3. If a wall separates two different systems, for instance, the juxtaposition of X and Y , $X \oplus Y$, the sudden removal of the wall can cause a sudden expansion, compression, or turbulence. To remove a wall with no mechanical work, the two states must be mechanically balanced, meaning that the relevant parameters, such as pressures, agree on both sides.

Definition 1.3.2 (Adiabatic Walls and Isolated Systems). A wall is called adiabatic iff it prevents any energy transfer other than mechanical work between the system and the ambient environment. Since the concept of “heat” is not yet introduced, we regard an adiabatic wall as a physical constraint that blocks all non-mechanical interactions across the boundary.

A system is called isolated iff it does not interact with its environment in any way. Experimentally, an isolated system is realized by enclosing it entirely within an ideal double wall with a vacuum, such as a thermos.

Definition 1.3.3 (Postulate: Equilibrium States of Adiabatic Systems). Let X be a thermodynamic system. By enclosing X within adiabatic walls, we isolate it from its environment. Fix its extensive parameters X^1, \dots, X^n . We postulate that the isolated system will eventually become an equilibrium state of the following form:

$$\left(T; \begin{pmatrix} X^1 \\ \vdots \\ X^n \end{pmatrix} \right), \quad (1.12)$$

where T represents the equilibrium “temperature,” a parameter determined solely by the initial state of X . Such a relaxation of a system under thermal isolation is sometimes referred to as the “minus first law” of thermodynamics.

We further assume that the equilibrium “temperature” is an intensive parameter. Namely, for any scale factor $\lambda > 0$, the scaled system λX becomes its equilibrium state

$$\left(T; \begin{pmatrix} \lambda X^1 \\ \vdots \\ \lambda X^n \end{pmatrix} \right). \quad (1.13)$$

Thus, under the scaling $X \mapsto \lambda X$, the equilibrium “temperature” remains unchanged.

Remark 4 (Positive “Temperature”). When using degrees Celsius, add 273.15; or when using degrees Fahrenheit, add 459.67, so that $T > 0$. See SI Units – Temperature.⁴

⁴<https://www.nist.gov/pml/owm/si-units-temperature>

Chapter 2

Adiabatic Processes

We now consider processes in which a system is isolated from its environment.

2.1 Adiabatic and Quasistatic Processes

Definition 2.1.1 (Adiabatic and Quasistatic Adiabatic Processes). Let $X_1 \mapsto X_2$ be a process between two states of a system X . If the system is enclosed within adiabatic walls, it is thermally isolated from the environment. Under this adiabatic condition, the transition of thermodynamic states is denoted by

$$(T_1; X_1) \xrightarrow{a} (T_2; X_2), \quad (2.1)$$

where both the initial and the final states are equilibrium states. For a given initial “temperature” T_1 and the initial equilibrium state $(T_1; X_1)$, the final equilibrium state X_2 , the final state X_2 uniquely determines the final “temperature” along the adiabatic process.

Note that an adiabatic process, physically, does not have to be gentle, or “static” or anything of the kind. It can be arbitrarily violent!¹

If the process is so slow that not only initial and final states, but also all intermediate states, remain in equilibrium, then such a virtual process is called quasistatic. We denote a quasistatic adiabatic process by

$$(T_1; X_1) \xrightarrow{qa} (T_2; X_2). \quad (2.2)$$

Quasi-static processes are done slowly enough that the system remains at thermodynamic equilibrium at each instant, despite the fact that the system changes over time. The thermodynamic equilibrium of the system is necessary for the system to have well-defined values

¹Elliott H. Lieb and Jakob Yngvason “A Guide to Entropy and the Second Law of Thermodynamics”

of macroscopic properties such as the temperature and the pressure of the system at each instant of the process. Therefore, quasi-static processes can be shown as well-defined paths in the state space of the system.²

As basic postulates of thermodynamics, we assume the following for quasistatic adiabatic processes:

- Continuity of temperature

The final “temperature” of a quasistatic adiabatic process $(T_1; X_1) \xrightarrow{\text{qa}} (T_2; X_2)$ depends continuously on the final state X_2 :

$$X_2 \dashrightarrow X_1 \Rightarrow T_2 \dashrightarrow T_1. \quad (2.3)$$

In other words, the “temperature” function t satisfies $\lim_{X_2 \rightarrow X_1} t(X_2) = t(X_1)$, where $t(X_1) = T_1$ and $t(X_2) = T_2$.

- Existence of inverse processes

Every quasistatic adiabatic process $(T_1; X_1) \xrightarrow{\text{qa}} (T_2; X_2)$ has an inverse, $(T_1; X_1) \xleftarrow{\text{qa}} (T_2; X_2)$. Both the forward and the inverse processes are quasistatic. Hence, we denote

$$(T_1; X_1) \xleftrightarrow{\text{qa}} (T_2; X_2). \quad (2.4)$$

Remark 5. We will give another characterization of adiabatic processes in Definition 2.1.3 in terms of energy.

Definition 2.1.2 (Postulate: Existence of “Temperature” Increasing Adiabatic Process). Let $(T_1; X)$ be an equilibrium state. For any $T_2 > T_1$, we postulate that there exists an adiabatic process that keeps the extensive parameters fixed:

$$(T_1; X) \xrightarrow{a} (T_2; X). \quad (2.5)$$

During this process, positive work must be done on the system; equivalently, the work done by the system is negative.

Remark 6. This principle is consistent with classical experiments on the inter-conversion of mechanical work and “heat,” such as Joule’s experiment, see, for example, December 1840: Joule’s abstract on converting mechanical power into heat³, College Physics 2e §14.1 Heat, and University Physics Volume 2 §1.4 Heat Transfer, Specific Heat, and Calorimetry.

Lemma 2.1.1. *Let X_1, X_2 be physically accessible states, i.e., there exist operations connecting them: $X_1 \mapsto X_2$ and $X_2 \mapsto X_1$. Then, for any $T_1, T_2 > 0$, at least either*

$$(T_1; X_1) \xrightarrow{a} (T_2; X_2) \quad (2.6)$$

²University Physics Volume 2 §3.4 Thermodynamic Processes

³<https://www.aps.org/publications/apsnews/200912/physicshistory.cfm>

or

$$(T_1; X_1) \xleftarrow{a} (T_2; X_2) \quad (2.7)$$

exists.

Proof. By assumption, there exists a quasistatic adiabatic process

$$(T_1; X_1) \xrightarrow{\text{qa}} (T'; X_2), \quad (2.8)$$

where T' is, a priori unknown, final “temperature” of this process.

- $T' < T_2$ case

If $T' < T_2$, by Definition 2.1.2, there is an adiabatic process

$$(T'; X_2) \xrightarrow{a} (T_2; X_2). \quad (2.9)$$

Combining these two processes yields the desired adiabatic process:

$$(T_1; X_1) \xrightarrow{\text{qa}} (T'; X_2) \xrightarrow{a} (T_2; X_2). \quad (2.10)$$

- $T' \geq T_2$ case

If $T' = T_2$, we obtain the desired adiabatic process, $(T_1; X_1) \xrightarrow{\text{qa}} (T' = T_2; X_2)$. So we may suppose $T' > T_2$. By Definition 2.1.1, the quasistatic adiabatic process is invertible. Hence, there is

$$(T_1; X_1) \xleftarrow{\text{qa}} (T'; X_2). \quad (2.11)$$

Since $T_2 < T'$, we can construct

$$(T_2; X_2) \xrightarrow{a} (T'; X_2) \xrightarrow{\text{qa}} (T_1; X_1). \quad (2.12)$$

■

Definition 2.1.3 (Postulate: First Law of Thermodynamics). We postulate that, for an adiabatic process, the work done by the system depends only on the initial and final states, regardless of the “path” connecting them.

In other words, since works behave like “flows,” there is a corresponding state quantity “stock” for each state. We call such “stocks” the internal energies. Let $U(T_1; X_1)$ denote the internal energy of the initial state and $U(T_2; X_2)$ the internal energy of the final state:

$$U(T_1; X_1) \xrightarrow[\Downarrow W_{\text{ad}}]{\text{.....}} U(T_2; X_2) \quad W_{\text{ad}} = U(T_1; X_1) - U(T_2; X_2). \quad (2.13)$$

For a system, we fix a reference equilibrium state (T_*, X_*) , where X_* is physically accessible from the states we consider. For a scaled system λX , $\lambda > 0$, the corresponding reference is $(T_*, \lambda X_*)$. By Lemma 2.1.1, either the forward

process $(T_*, \lambda X_*) \xrightarrow{a} (T; \lambda X)$ or the backward process $(T_*, \lambda X_*) \xleftarrow{a} (T; \lambda X)$ exists. We then define

$$U(T; \lambda X) := \begin{cases} -W_{\text{ad}} \left((T_*, \lambda X_*) \xrightarrow{a} (T; \lambda X) \right) & \text{if } (T_*, \lambda X_*) \xrightarrow{a} (T; \lambda X) \text{ exists} \\ W_{\text{ad}} \left((T_*, \lambda X_*) \xleftarrow{a} (T; \lambda X) \right) & \text{otherwise.} \end{cases} \quad (2.14)$$

We also assume that U has suitable analytical properties, for instance, U is continuous:

$$(T_1; X_1) \dashrightarrow (T_2; X_2) \Rightarrow U(T_1; X_1) \dashrightarrow U(T_2; X_2). \quad (2.15)$$

See College Physics §15.1 The First Law of Thermodynamics, University Physics Volume 2 §3.3 First Law of Thermodynamics, and Definition 3.1.1.

Lemma 2.1.2. *For a fixed system X , its internal energy U is an increasing function of the “temperature.” Namely,*

$$T_1 < T_2 \Rightarrow U(T_1; X) < U(T_2; X). \quad (2.16)$$

Proof. By Definition 2.1.2, for any equilibrium state $(T_1; X)$, and any $T_2 > T_1$, there exists an adiabatic process

$$(T_1; X) \xrightarrow{a} (T_2; X), T_1 < T_2. \quad (2.17)$$

Along this adiabatic process, some positive work must be done on the system. Hence, the work done by the system is negative:

$$U(T_1; X) \xrightarrow[\downarrow W < 0]{} U(T_2; X) \quad (2.18)$$

Thus, $W = U(T_1; X) - U(T_2; X) < 0$. ■

Definition 2.1.4 (Heat Capacity at Constant Volume). For a thermodynamic system in an equilibrium state $(T; X)$, the heat capacity at constant volume is defined by

$$C_V(T; X) := \frac{\partial U(T; X)}{\partial T}. \quad (2.19)$$

This partial derivative is taken with all extensive parameters, particularly the volume V in X , fixed. See College Physics §14.2 Temperature Change and Heat Capacity and University Physics Volume 2 §3.5 Heat Capacities of an Ideal Gas.

2.2 Reversible Processes

Definition 2.2.1 (Reversible Processes). An adiabatic process $(T_1; X_1) \xrightarrow{a} (T_2; X_2)$ is called reversible iff a backward adiabatic process $(T_1; X_1) \xleftarrow{a} (T_2; X_2)$ exists. If such an inverse process does not exist, or if all backward processes are not adiabatic, then the forward process is called irreversible.

By Definition 2.1.1, a quasistatic adiabatic process is reversible.

Definition 2.2.2 (Postulate: Planck's Statement). For an adiabatic process, if the extensive parameters remain constant, $(T_1; X) \xrightarrow{a} (T_2; X)$, the internal energy never decreases, $U(T_1; X) \leq U(T_2; X)$. Consequently, $T_1 \leq T_2$ holds, by Lemma 2.1.2.

Lemma 2.2.1. *The “temperature-increasing,” $T_1 < T_2$, adiabatic process in Definition 2.1.2 $(T_1; X) \xrightarrow{a} (T_2; X)$ is irreversible.*

Proof. If a Joule's experiment were reversible, there would be a backward process from (T_2, X) to (T_1, X) with $T_2 > T_1$. By Lemma 2.1.2, along with the backward adiabatic process, $U(T_2, X) > U(T_1, X)$, which is contradictory to Definition 2.2.2. ■

Chapter 3

Isothermal Processes

We consider processes that occur under a constant “temperature” condition, from $(T; X_1)$ to $(T; X_2)$, for instance. Experimentally, such a process is achieved by maintaining thermal contact with a “temperature” reservoir – also known as a “heat” bath or a thermostat – such as the atmosphere and the ocean of the Earth. The essential feature of a “heat” bath is its large size.

An isothermal process is a change in the state of the system at a constant temperature. This process is accomplished by keeping the system in thermal equilibrium with a large heat bath during the process. Recall that a heat bath is an idealized “infinitely” large system whose temperature does not change. In practice, the temperature of a finite bath is controlled by either adding or removing a finite amount of energy as the case may be.¹

3.0 Heat Baths – Construction

Let X_1, X_2 be states of a system X , let Y be a state of another system, and $\lambda > 0$ be a scaling parameter. Consider $X_1 \oplus \lambda Y$ and a fixed process of the subsystem $X_1 \mapsto X_2$. If the system $X_1 \oplus \lambda Y$ is kept isolated from the external environment, then the overall adiabatic process can be written in the following form:

$$(T; X_1 \oplus \lambda Y) \xrightarrow{a} (T_\lambda; X_2 \oplus \lambda Y), \quad (3.1)$$

where T_λ is a resulting final “temperature.” Both the final “temperature” and the work W_λ done by the whole system during this adiabatic process

$$U(T; X_1 \oplus \lambda Y) \xrightarrow[\Downarrow W_\lambda]{\dots\dots\dots} U(T_\lambda; X_2 \oplus \lambda Y) \quad (3.2)$$

depend on the scaling parameter $\lambda > 0$.

¹University Physics Volume 2 §3.4 Thermodynamic Processes

Definition 3.0.1 (Heat). Let us define the heat Q_λ from λY to X_1 by

$$Q_\lambda := U(T; \lambda Y) - U(T_\lambda; \lambda Y) = \lambda (U(T; Y) - U(T_\lambda; Y)). \quad (3.3)$$

That is, the heat Q_λ is characterized by the following diagrams:

$$\left\{ \begin{array}{ccc} U(T; \lambda Y) & \xrightarrow{\quad\quad\quad} & U(T_\lambda; \lambda Y) \\ & \Downarrow Q_\lambda & \\ U(T; X_1) & \xrightarrow{\quad\quad\quad} & U(T_\lambda; X_2) \\ & \Downarrow W_\lambda & \end{array} \right. \quad (3.4)$$

The heat Q_λ is regarded as a thermal interaction – energy exchange – between X and λY , see Remark 2.

Lemma 3.0.1 (Thermal Contact and Transferred Energy). *Let W_X denote the loss of the internal energy of the subsystem:*

$$U(T; X_1) \xrightarrow{\quad\quad\quad} U(T_\lambda; X_2) \quad \Downarrow W_X \quad (3.5)$$

Then, Q_λ can be regarded as the energy transfer from the finite-sized “heat bath” λY to the system X :

$$W_\lambda = W_X + Q_\lambda = U(T; X_1) - U(T_\lambda; X_2) + Q_\lambda. \quad (3.6)$$

Remark 7. In our formulation, the mechanical equivalence of heat and energy is manifest, see College Physics §14.1 Heat, University Physics Volume 2 §1.4 Heat Transfer, Specific Heat, and Calorimetry, University Physics Volume 2 §3.2 Work, Heat, and Internal Energy, Remark 6 and Definition 3.1.1.

Proof. If we consider the subsystems separately, it is rather obvious:

$$U(T; \lambda Y) \xrightarrow{\quad\quad\quad} U(T_\lambda; \lambda Y) \quad \Downarrow Q_\lambda \quad (3.7)$$

$$U(T; X_1) \xrightarrow{\quad\quad\quad} U(T_\lambda; X_2) \quad \Downarrow W_X$$

since $Q_\lambda + W_X$ is the net work W_λ done by the composite system, $Q_\lambda + W_X = W_\lambda$.

For later analysis, let us introduce the notation $((T; X)|(T'; \lambda Y))$ to denote that X and λY are separated by an adiabatic wall $|$, where we use T' for the temperature of λY system. Suppose the composite system is isolated. If we slowly replace the adiabatic wall $|$ by a diathermal wall, we obtain the corresponding adiabatic process

$$((T; X)|(T'; \lambda Y)) \xrightarrow{a} (\tilde{T}; X \oplus \lambda Y), \quad (3.8)$$

where \tilde{T} is the final temperature of the composite system through the adiabatic process. Since no work is done during this process, see Definition 1.3.1, we may apply the energy conservation stated in Definition 2.1.3:

$$U(T; X) + U(T'; \lambda Y) = U(\tilde{T}; X \oplus \lambda Y) = U(\tilde{T}; X) + U(\tilde{T}; \lambda Y). \quad (3.9)$$

Rearranging, we obtain the transferred energy from λY to X , namely the gain of the internal energy of X and the loss of the internal energy of λY :

$$U(\tilde{T}; X) - U(T; X) = U(T'; \lambda Y) - U(\tilde{T}; \lambda Y). \quad (3.10)$$

Therefore, through the process in (3.4), where $\tilde{T} = T_\lambda$ and $T' = T$, the loss of internal energy $Q_\lambda = U(T; \lambda Y) - U(T_\lambda; \lambda Y)$ of λY is indeed the transferred energy from λY to X . Hence, the heat Q_λ is the amount of energy entering the system X in a mode that can be blocked by an adiabatic wall |. ■

To construct a heat bath as a constant T -reservoir, we require the thermal interaction between systems to behave regularly in the thermodynamic limit.

Definition 3.0.2 (Postulate: Finite Heat Transfer in Thermodynamic Limit). We assume $\lim_{\lambda \rightarrow \infty} Q_\lambda$ exists and is finite. That is, even when we take $\lambda \rightarrow \infty$ limit, the heat transfer Q_λ does not diverge:

$$\lim_{\lambda \rightarrow \infty} Q_\lambda < +\infty. \quad (3.11)$$

In other words, the thermal interaction between X and λY remains well-behaved in the thermodynamic limit $\lambda \rightarrow \infty$.

Lemma 3.0.2. *In the thermodynamic limit $\lambda \rightarrow \infty$, the final “temperature” of the system remains constant, $\lim_{\lambda \rightarrow \infty} T_\lambda = T$.*

Proof. Let $\epsilon > 0$. By the standard definition of convergence via ϵ - δ , $t_\lambda \rightarrow t$ as $\lambda \rightarrow +\infty$ means that there exists $\lambda_\epsilon > 0$ such that

$$\lambda \geq \lambda_\epsilon \Rightarrow |t_\lambda - t| < \epsilon. \quad (3.12)$$

Suppose, for contradiction that $T \neq \lim_{\lambda \rightarrow \infty} T_\lambda$. Then, for any $\lambda > 0$, there exists $\delta > 0$ such that $|T_\lambda - T| \geq \delta$. From Lemma 2.1.2, the mapping $T \mapsto U(T; Y)$ is an increasing function. Hence, if $T_\lambda \neq T$, we have $U(T; Y) - U(T_\lambda; Y) \neq 0$, so there exists some $\delta' > 0$ with $|U(T; Y) - U(T_\lambda; Y)| \geq \delta'$. Therefore, as $\lambda \rightarrow +\infty$, the heat transfer would satisfy

$$|Q_\lambda| = \lambda |U(T; Y) - U(T_\lambda; Y)| \geq \lambda \delta' \rightarrow +\infty, \quad (3.13)$$

which contradicts the assumption in Definition 3.0.2. ■

In this limit $\lambda \rightarrow +\infty$, the scaled system λY acts as the environmental heat bath, maintaining the “temperature” of the system X constant. Processes occurring under constant “temperature” are called isothermal:

3.1 Isothermal Processes and Heats

Definition 3.1.1 (Heat Baths and Isothermal Processes). For a process $X_1 \mapsto X_2$ of a subsystem of a composite system $X \oplus \lambda Y, \lambda > 0$, if we identify X as a system and λY as the environment, λY under the thermodynamic limit $\lambda \dashrightarrow +\infty$ is called a heat bath or T -reservoir. In this limit, the work (3.6) through $X_1 \mapsto X_2$ converges:

$$W := \lim_{\lambda \rightarrow \infty} W_\lambda = \lim_{\lambda \rightarrow \infty} U(T; X_1) - U(T_\lambda; X_2) + Q_\lambda = U(T; X_1) - U(T; X_2) + Q. \quad (3.14)$$

This relation expresses the energy conservation for a process $X_1 \mapsto X_2$ under a constant T -environment:

$$U(T; X_1) \xrightarrow[\Downarrow W]{\Downarrow Q} U(T; X_2). \quad (3.15)$$

This relation is also called the first law of thermodynamics– energy conservation – see Definition 2.1.3.

For a general process $(T_1; X_1) \rightarrow (T_2; X_2)$, by Lemma 2.1.1, both $(T_1; X_1)$ and $(T_2; X_2)$ are adiabatically connected. Let W_{general} be the work done by the system along $(T_1; X_1) \rightarrow (T_2; X_2)$. If $(T_1; X_1) \xrightarrow{a} U(T_2; X_2)$ exists, we can measure the loss of the internal energy $U(T_1; X_1) - U(T_2; X_2)$ through the adiabatic work, $W_{\text{ad}} = U(T_1; X_1) - U(T_2; X_2)$. We call the difference W_{general} and W_{ad} the heat flow onto the system, $Q_{\text{general}} = W_{\text{general}} - W_{\text{ad}}$.

Remark 8 (Impossibility of Perpetual Motion Machine of First Kind). As a direct consequence of energy conservation, no “engine” can produce positive work without an external energy source. That is, a perpetual motion machine of the first kind is impossible.

It is worth noting that the difference $Q - W = U(T; X_2) - U(T; X_1)$ depends only on the initial and the final states, not on the specific path from X_1 to X_2 under the constant T , see Figure 3.7 in University Physics Volume 2 §3.3 First Law of Thermodynamics.

Definition 3.1.2 (Isothermal Processes). As established in Definition 3.1.1, an operation $X_1 \mapsto X_2$ under constant “temperature” T an isothermal process:

$$(T; X_1) \xrightarrow{i} (T; X_2). \quad (3.16)$$

An isothermal process is called a quasistatic isothermal process iff it is so slow that any intermediate state can be seen as an equilibrium state:

$$(T; X_1) \xrightarrow{\text{qi}} (T; X_2). \quad (3.17)$$

Any quasistatic isothermal process has the inverse

$$(T; X_1) \xleftrightarrow{\text{qi}} (T; X_2), \quad (3.18)$$

see Definition 2.1.1.

Definition 3.1.3 (Cycles). A process is called a cycle iff both initial and final states coincide.

Theorem 3.1.1 (Kelvin’s Statement). *For any isothermal cycle, the work W_{cyc} done by the system is non-positive:*

$$W_{cyc} \leq 0. \quad (3.19)$$

Proof. Let X and Y be systems and $\lambda > 0$. Consider a cyclic operation $X \mapsto X$ and the corresponding adiabatic process for $X \oplus \lambda Y$:

$$(T; X \oplus \lambda Y) \xrightarrow{a} (T_\lambda; X \oplus \lambda Y). \quad (3.20)$$

By Definition 2.2.2, we obtain $T \leq T_\lambda$. Hence, from Lemma 2.1.2,

$$\begin{aligned} U(T; X) &\leq U(T_\lambda; X) \\ U(T; Y) &\leq U(T_\lambda; Y) \end{aligned} \quad (3.21)$$

The transferred heat Q_λ in Definition 3.0.1 satisfies

$$Q_\lambda = \lambda (U(T; Y) - U(T_\lambda; Y)) \leq 0, \quad (3.22)$$

Therefore, the work done by the system is

$$W_\lambda := U(T; X) - U(T_\lambda; X') + Q_\lambda \leq 0. \quad (3.23)$$

If we take $\lambda \rightarrow +\infty$ limit, we obtain the desired result, $W := \lim_{\lambda \rightarrow \infty} W_\lambda \leq 0$, since $T_\lambda \rightarrow T$ if $\lambda \rightarrow \infty$ and, hence, the transition $X \mapsto X$ becomes an isothermal cyclic process. ■

Remark 9 (Impossibility of Perpetual Motion Machine of Second Kind). As a consequence, no perpetual motion machine of the second kind – no cyclic process under constant “temperature” can produce positive work without external input.

Lemma 3.1.1. *The work done by a quasistatic isothermal cycle is zero.*

Proof. Let $(T; X) \xrightarrow{qi} (T; X)$ be a quasistatic isothermal cycle and let W denote the work done along this cycle. By Theorem 3.1.1, the work along any isothermal cycle is non-positive, $W \leq 0$. By Definition 3.1.2, there exists a backward process, $(T; X) \xleftarrow{qi} (T; X)$. Since this backward process is cyclic, the work done by this inverse cycle is non-positive, $-W \leq 0$. ■

3.2 Maximum Work and Helmholtz Free Energy

A central goal of thermodynamics is to determine the conditions under which a system can deliver the maximum available work, often referred to as the “exergy” or the work potential.

3.2.1 Maximum Work

Definition 3.2.1 (Maximum Work). Let X_1, X_2 be two states of a system. The maximum work obtainable in a transition $X_1 \mapsto X_2$ at constant T is defined by

$$W_{\max}(T; X_1 \mapsto X_2) := \max \left\{ W \mid U(T; X_1) \xrightarrow[\downarrow W]{\downarrow Q} U(T; X_2) \right\}, \quad (3.24)$$

where max is taken over all isothermal processes from X_1 to X_2 .

Mathematically, $\left\{ W \mid U(T; X_1) \xrightarrow[\downarrow W]{\downarrow Q} U(T; X_2) \right\}$ could have no maximum element. Hence, it must be rather defined via sup of the least upper bound. As we will see in Theorem 3.2.1, however, there exists a desired isothermal process that achieves $W_{\max}(T; X_1 \mapsto X_2)$.

Theorem 3.2.1 (Principle of Maximum Work). *The maximum work is achieved during a quasistatic isothermal process, $(T; X_1) \xrightarrow{qi} (T; X_2)$.*

Proof. Let W denote the work done by the system during a quasistatic isothermal process, and let W' denote the work during an arbitrary isothermal process connecting the same states. We will show $W' \leq W$. By Definition 3.1.2, the quasistatic process has a reversible inverse $(T; X_1) \xleftarrow{qi} (T; X_2)$. Since

$$(T; X_1) \xrightleftharpoons[qi]{i} (T; X_2) \quad (3.25)$$

forms an isothermal cycle on $(T; X_1)$, we may apply Theorem 3.1.1. The net work done by this cycle is non-positive, $W' - W \leq 0$. ■

Corollary 3.2.1.1 (Path Independence of Maximum Work). *The maximum work $W_{\max}(T; X_1 \mapsto X_2)$ is path-independent.*

Proof. By Theorem 3.2.1, the maximum work $W_{\max}(T; X_1 \mapsto X_2)$ is achieved by a quasistatic isothermal process. Therefore, it suffices to show the work done by any quasistatic process is the same.

Consider two quasistatic isothermal processes:

$$(T; X_1) \xrightleftharpoons[qi]{qi} (T; X_2) \quad (3.26)$$

By combining the forward first process and the backward second process, we have a quasistatic isothermal cycle:

$$(T; X_1) \xrightleftharpoons[qi]{qi} (T; X_2) \quad (3.27)$$

By Lemma 3.1.1, the net work done by such a cycle is zero. Hence, the work done along two quasistatic processes must be equal. ■

Exercise 3.2.1 (Properties of Maximum Work). Show the following properties of maximum work:

1. Scaling

For $\lambda > 0$,

$$W_{\max}(T; \lambda X_2 \mapsto \lambda X_1) = \lambda W_{\max}(T; X_1 \mapsto X_2). \quad (3.28)$$

2. Reversibility

For the reverse process of $X_1 \mapsto X_2$,

$$W_{\max}(T; X_2 \mapsto X_1) = -W_{\max}(T; X_1 \mapsto X_2). \quad (3.29)$$

3. Additive for consecutive processes

For a sequence of processes $X_1 \mapsto X_2$ and $X_2 \mapsto X_3$,

$$W_{\max}(T; X_1 \mapsto X_3) = W_{\max}(T; X_1 \mapsto X_2) + W_{\max}(T; X_2 \mapsto X_3). \quad (3.30)$$

4. Additivity for independent systems

If we juxtapose two quasistatic processes:

$$\begin{aligned} (T; X_1) &\xrightarrow{\text{qi}} (T; X_2) \\ (T; Y_1) &\xrightarrow{\text{qi}} (T; Y_2) \end{aligned} \quad (3.31)$$

namely, $(T; X_1 \oplus Y_1) \xrightarrow{\text{qi}} (T; X_2 \oplus Y_2)$, the maximum work is additive:

$$W_{\max}(T; X_1 \oplus Y_1 \mapsto X_2 \oplus Y_2) = W_{\max}(T; X_1 \mapsto X_2) + W_{\max}(T; Y_1 \mapsto Y_2) \quad (3.32)$$

3.2.2 Helmholtz Free Energy

By Corollary 3.2.1.1, the maximum work $W_{\max}(T; X_1 \mapsto X_2)$ is path-independent for any isothermal transition $(T; X_1)$ to $(T; X_2)$. This allows us to introduce a corresponding stock associated with the flow of maximum work.

Definition 3.2.2 (Helmholtz Free Energy). Since $W_{\max}(T; X_1 \mapsto X_2)$ depends only on the initial and final states, we may define a state function F – the Helmholtz free energy – via the stock-flow diagram

$$F[T; X_1] \begin{array}{c} \cdots \cdots \cdots \searrow \\ \downarrow W_{\max} \end{array} F[T; X_2]. \quad (3.33)$$

That is, Helmholtz free energy is defined so that the maximum available work in an isothermal process equals the loss of F , $W_{\max}(T; X_1 \mapsto X_2) = F[T; X_1] - F[T; X_2]$. Hence, Helmholtz free energy represents the maximum useful work

obtainable from a system at constant temperature. This is sometimes referred to as the principle of maximum work – no isothermal process can extract more work from a system than the loss of the Helmholtz free energy.

As with internal energy in Definition 2.1.3, we choose a reference state $(T_*; X_*)$ accessible to all states under consideration. For a scaled system $(T; \lambda X)$, $\lambda > 0$, we use the corresponding scaled state $(T_*; \lambda X_*)$ and define

$$F[T; \lambda X] := W_{\max}(T; \lambda X \mapsto \lambda X_*). \quad (3.34)$$

Finally, we assume several mild analytical conditions such as continuity in “temperature:”

$$T_1 \dashrightarrow T_2 \Rightarrow F[T_1; X] \dashrightarrow F[T_2; X]. \quad (3.35)$$

3.3 Equation of State and Pressure

Let us consider a state $\left(\frac{V}{N}\right)$ introduced in Example 1.2.1.

Example 3.3.1 (Fluids – Pressure). Let $V = Al$ be the volume of a cylindrical cross-section A and height l , equipped with a movable piston. Consider the following quasistatic isothermal process:

$$\left(T; \left(\frac{V}{N}\right)\right) \xrightarrow{\text{qi}} \left(T; \left(\frac{V + \Delta V}{N}\right)\right), \quad (3.36)$$

where $V + \Delta V = A(l + \Delta l)$.

Let W be the mechanical work W done by the system during this small displacement Δl , and let f be the force the system exerts on the piston. If Δl is sufficiently small, neglecting terms of order $(\Delta l)^2$, we have

$$W = f\Delta l = \frac{f}{A}A\Delta l = p\Delta V, \quad (3.37)$$

where $pA = f$ defines the pressure p . Because the process is quasistatic isothermal, $W = W_{\max}$. Thus, the pressure may be extracted from

$$\begin{aligned} p\left(T; \left(\frac{V}{N}\right)\right) &:= \lim_{\Delta V \rightarrow +0} \frac{W_{\max}\left(T; \left(\frac{V}{N}\right) \mapsto \left(\frac{V + \Delta V}{N}\right)\right)}{\Delta V} \\ &= - \lim_{\Delta V \rightarrow +0} \frac{F\left[T; \left(\frac{V + \Delta V}{N}\right)\right] - F\left[T; \left(\frac{V}{N}\right)\right]}{\Delta V} \\ &= - \frac{\partial F\left[T; \left(\frac{V}{N}\right)\right]}{\partial V}. \end{aligned} \quad (3.38)$$

The pressure of the system is given by the following state function:

$$\left(T; \left(\frac{V}{N}\right)\right) \mapsto p\left(T; \left(\frac{V}{N}\right)\right) \quad (3.39)$$

which is called the equation of state.

Exercise 3.3.1 (Intensive Property). Show that pressure is an intensive parameter. Namely, for any $\lambda > 0$,

$$p\left(T; \lambda \left(\frac{V}{N}\right)\right) = p\left(T; \left(\frac{V}{N}\right)\right). \quad (3.40)$$

Example 3.3.2 (Ideal Gas). As discussed in Remark 1, the pressure of a fluid under “temperature” T satisfies

$$p\left(T; \left(\frac{V}{N}\right)\right) \approx \frac{NRT}{V}. \quad (3.41)$$

A simple toy model of gas is the ideal gas, which is characterized by the following properties:

1. Equation of state

The above approximation is indeed exact:

$$p\left(T; \left(\frac{V}{N}\right)\right) = \frac{NRT}{V}. \quad (3.42)$$

2. Heat capacity

The heat capacity C_V , defined in Definition 2.1.4, is proportional only to the amount of substance, independent of T :

$$C_V\left(T; \left(\frac{V}{N}\right)\right) = cNR. \quad (3.43)$$

This is well-known Regnault’s law.

See College Physics §13.3 The Ideal Gas Law and University Physics Volume 2 §3.5 Heat Capacities of an Ideal Gas.

Recalling (3.38), we compute Helmholtz free energy of the ideal gas:

$$F\left[T; \left(\frac{V}{N}\right)\right] - F\left[T; \left(\frac{V_*}{N}\right)\right] = - \int_{V_*}^V \frac{NRT}{V'} dV' = -NRT \ln \frac{V}{V_*}, \quad (3.44)$$

where we select V_* such that

$$F\left[T; \left(\frac{V_*}{N}\right)\right] = 0, \quad (3.45)$$

see Definition 3.2.2.

Note that \ln stands for \log , see Algebra and Trigonometry 2e §6.3 Logarithmic Functions and Algebra and Trigonometry 2e §6.5 Logarithmic Properties.

For convenience, we may further select a reference volume proportional to the amount of substance, $V_* = v(T)N$, where $v(T)$ is a positive value. With this choice, we have

$$F\left[T; \left(\frac{V}{N}\right)\right] = -NRT \ln \frac{V}{v(T)N}. \quad (3.46)$$

Exercise 3.3.2. Plot $x \mapsto -\ln(x)$ on $(0, +\infty)$.

Apply this to the ideal gas (3.46), one can show that $V \mapsto F\left[T; \left(\frac{V}{N}\right)\right]$ is a decreasing function. That is, for the same amount of ideal gas, the smaller the volume V , the more work the system can perform.

By Definition 2.1.4,

$$U\left(T; \left(\frac{V}{N}\right)\right) - U\left(T_*; \left(\frac{V}{N}\right)\right) = \int_{T_*}^T cNR dT' = cNR(T - T_*) \quad (3.47)$$

where we set, as a reference,

$$U\left(T_*; \left(\frac{V}{N}\right)\right) = 0, \quad (3.48)$$

see Definition 2.1.3. Thus, we may write

$$U\left(T; \left(\frac{V}{N}\right)\right) = cNRT + Nu, \quad (3.49)$$

where $u = -cRT_*$ is a constant. In particular, the internal energy of an ideal gas remains constant under isothermal processes.

Now, consider a quasistatic adiabatic process:

$$\left(T; \left(\frac{V}{N}\right)\right) \xrightarrow{\text{qa}} \left(T'; \left(\frac{V'}{N}\right)\right) \quad (3.50)$$

Let $\Delta V := V' - V$ and $\Delta T := T' - T$. Let p denote the mechanical pressure of the ideal gas. The work ΔW done by the ideal gas is, up to terms of order $(\Delta V)^2$,

$$\Delta W = p\Delta V = \frac{NRT}{V}\Delta V, \quad (3.51)$$

where we used the equation of state. By energy conservation, in this infinitesimal adiabatic process,

$$U(T; V, N) \xrightarrow[\Downarrow \Delta W]{\text{.....}} U(T'; V', N) \quad (3.52)$$

so that we have

$$\Delta W = U\left(T; \left(\frac{V}{N}\right)\right) - U\left(T'; \left(\frac{V'}{N}\right)\right) = -cNR\Delta T. \quad (3.53)$$

Hence, we obtain the following differential equation:

$$\frac{NRT}{V}dV = -cNRdT. \quad (3.54)$$

Separating variables:

$$c \int \frac{dT}{T} = - \int \frac{dV}{V}, \quad (3.55)$$

we find the Poisson relation for an ideal gas:

$$T^c V = \text{constant under an adiabatic process.} \quad (3.56)$$

Example 3.3.3 (The heat capacity of an ideal gas at constant pressure). Consider a fixed amount of an ideal gas $\left(\frac{V}{N}\right)$ contained in cylindrical chamber of cross-sectional area A and height h , so that $V = Ah$. Suppose the top panel is a movable piston supporting a mass m under gravity $|g|$. Then the gas is under constant external pressure $p = \frac{m|g|}{A}$. Now

$$pV = pAh = m|g|h. \quad (3.57)$$

Consider the composite system, which consists of the ideal gas and the mechanical system of a movable piston under constant pressure p . Suppose an external source gives ΔQ of heat onto the fluid system, causing a mechanical process $V \mapsto V + \Delta V$ under constant pressure p and Δh through $p\Delta V = m|g|\Delta h$. Recalling that N remains constant, the composite system exchanges mechanical work $p\Delta V$:

$$\left\{ \begin{array}{ccc} U(T; V) & \xrightarrow{\downarrow \Delta Q} & U(T + \Delta T; V + \Delta V) \\ & \Downarrow p\Delta V & \\ pV & \xrightarrow{\quad} & p(V + \Delta V) \end{array} \right. \quad (3.58)$$

It follows $\Delta Q = p\Delta V + \Delta U$, where $\Delta U = U\left(T + \Delta T; \left(\frac{V + \Delta V}{N}\right)\right) - U\left(T; \left(\frac{V}{N}\right)\right)$.

If we suppose the external, mechanical pressure and the thermodynamic pressure of the ideal gas coincide,

$$\Delta Q = NR\Delta T + \Delta U = (c + 1)NR\Delta T \quad (3.59)$$

since the internal energy of an ideal gas does not depend on volume, see (3.49). Hence, the corresponding heat capacity at constant pressure of an ideal gas is given by $C_p = (c + 1)NR$.

Chapter 4

Heat and Carnot's Theorem

Definition 4.0.1 (Maximum Heat Transfer From Heat Bath). For an isothermal process, $(T; X_1) \xrightarrow{i} (T; X_2)$, define the maximum heat transfer $Q_{\max}(T; X_1 \mapsto X_2)$ from the T -reservoir to the system by

$$Q_{\max}(T; X_1 \mapsto X_2) := \max \left\{ Q \left| U(T; X_1) \xrightarrow[\Downarrow W]{\Downarrow Q} U(T; X_2) \right. \right\}, \quad (4.1)$$

where the max is taken over all isothermal processes connecting X_1 and X_2 . It follows immediately from Definition 3.2.1 and Definition 3.2.2 that

$$\begin{aligned} Q_{\max}(T; X_1 \mapsto X_2) &= W_{\max}(T; X_1 \mapsto X_2) + U(T; X_2) - U(T; X_1) \\ &= F[T; X_1] - F[T; X_2] + U(T; X_2) - U(T; X_1) \end{aligned} \quad (4.2)$$

By Theorem 3.2.1, $Q_{\max}(T; X_1 \mapsto X_2)$ is achieved by a quasistatic isothermal process $(T; X_1) \xrightarrow{qi} (T; X_2)$.

4.1 Generalized Isothermal Processes

Let us construct a generalized isothermal process with a T' -reservoir, namely, a process from (T, X_1) to (T', X_2) carried out under a constant “temperature” T' .

Theorem 4.1.1 (Generalized Isothermal Processes). *Consider the following processes:*

$$((T; X_1)|(T'; \lambda Y)) \xrightarrow{a} (\widetilde{T}_\lambda; X_1 \oplus \lambda Y) \xrightarrow{a} (T'_\lambda; X_2 \oplus \lambda Y), \quad (4.3)$$

where the first adiabatic process corresponds to the adiabatic wall removal in Lemma 3.0.1. Then, under the thermodynamic limit $\lambda \dashrightarrow +\infty$, we obtain a generalized isothermal process under T' -reservoir:

$$(T; X_1) \xrightarrow{i'} (T'; X_2). \quad (4.4)$$

Proof. The associated state transitions are as follows, see (3.4):

$$\left\{ \begin{array}{ccc} U(T'; \lambda Y) & \cdots \cdots \cdots & U(T'_\lambda; \lambda Y) \\ & \Downarrow Q'_\lambda & \\ U(T; X_1) & \cdots \cdots \cdots & U(T'_\lambda; X_2) \\ & \Downarrow W'_\lambda & \end{array} \right. \quad (4.5)$$

By Definition 3.0.2 and Lemma 3.0.2, both the heat transfer $Q'_\lambda = U(T; \lambda Y) - U(T'_\lambda; \lambda Y)$ and the work done by the whole system $W'_\lambda := U(T; X_1) - U(T'_\lambda; X_2) + Q'_\lambda$ have well-defined limits as $\lambda \rightarrow +\infty$. Thus, we obtain

$$U(T; X_1) \begin{array}{c} \Downarrow Q' \\ \cdots \cdots \cdots \\ \Downarrow W' \end{array} U(T'; X_2) \quad (4.6)$$

where $Q' := \lim_{\lambda \rightarrow \infty} Q'_\lambda$, $W' := \lim_{\lambda \rightarrow \infty} W'_\lambda$, and $T' = \lim_{\lambda \rightarrow \infty} T'_\lambda$. ■

Remark 10 (Wall-Removal i'-Process). If we take $X_2 = X_1$, the corresponding process is just an adiabatic wall removal $((T; X_1) | (T'; \lambda Y)) \xrightarrow{a} (\widetilde{T}_\lambda; X_1 \oplus \lambda Y)$. Its thermodynamic limit $\lambda \rightarrow +\infty$, namely

$$(T; X_1) \xrightarrow{i'} (T'; X_1) \quad (4.7)$$

does no work or requires no work, by Definition 1.3.1. Thus, in this special case $X_2 = X_1$, both the work done by the system and the work required to remove the wall vanish.

Corollary 4.1.1.1. *If a quasistatic adiabatic process $(T; X_1) \xleftarrow{qa} (T'; X_3)$ exists, then the maximum work done by the system from $(T; X_1)$ to $(T'; X_2)$ under a T' -reservoir is given by the following sequence of quasistatic processes:*

$$(T; X_1) \xrightarrow{qa} (T'; X_3) \xrightarrow{qi} (T'; X_2). \quad (4.8)$$

The same quasistatic process obtains the maximum heat from the environment.

Proof. Let W' be the work done by an arbitrary generalized isothermal process $(T; X) \xrightarrow{i'} (T'; X')$ under the T' -reservoir. Compare this process with the following sequence of quasistatic processes:

$$(T; X_1) \begin{array}{ccc} & \xrightarrow{i'} & \\ \xrightarrow{qa} & (T'; X_3) & \xrightarrow{qi} \\ & & \end{array} (T'; X_2) \quad (4.9)$$

The work W'_{qa} done by the first quasistatic adiabatic process is the loss of internal energy:

$$U(T; X_1) \begin{array}{c} \cdots \cdots \cdots \\ \Downarrow W'_{\text{qa}} \end{array} U(T'; X_3) \quad (4.10)$$

The second quasistatic isothermal process satisfies

$$U(T; X_3) \begin{array}{c} \Downarrow Q'_{\text{qi}} \\ \cdots \cdots \cdots \rightarrow \\ \Downarrow W'_{\text{qi}} \end{array} U(T'; X_2) \quad (4.11)$$

The total work W_q done by these quasistatic processes is $W_q = W'_{\text{qa}} + W'_{\text{qi}}$.

Reverse these quasistatic processes, and consider the following cycle:

$$(T; X_1) \xrightarrow{\text{qa}} (T'; X_3) \xrightarrow{\text{qi}} (T'; X_2) \xrightarrow{\text{i}'} (T; X_1) \quad (4.12)$$

Let W_{cyc} be the work done by the above cycle:

$$W_{\text{cyc}} = W' - W_q. \quad (4.13)$$

Since the entire cycle is under the T' -reservoir, we may apply Theorem 3.1.1, $W_{\text{cyc}} \leq 0$. Hence, $W' \leq W_q$.

Let Q' be the heat transfer from the T' -reservoir through $(T; X_1) \xrightarrow{\text{i}'} (T'; X_2)$, see (4.6). Computing the total work in terms of heat and changes in free energy:

$$\begin{aligned} 0 \geq W_{\text{cyc}} &= (Q' - U(T'; X_2) + U(T; X_1)) \\ &\quad - (U(T; X_1) - U(T'; X_3) + F[T'; X_3] - F[T'; X_2]) \\ &= Q' + F[T'; X_2] - F[T'; X_3] + U(T'; X_3) - U(T'; X_2) \\ &= Q' + Q_{\text{max}}(T' : X_2 \mapsto X_3). \end{aligned} \quad (4.14)$$

Hence, we conclude:

$$Q' \leq -Q_{\text{max}}(T' : X_2 \mapsto X_3) = Q'_{\text{qi}}, \quad (4.15)$$

showing that the quasistatic process yields the maximum heat transfer from the reservoir. \blacksquare

Definition 4.1.1 (Postulate: Adiabatic Accessible Lower “Temperature” State). Let $T > 0$, and X_0 be a state. We postulate that there exists a state $(T'; X_1)$ with $0 < T' < T$ such that a quasistatic adiabatic “temperature” decreasing process:

$$(T; X_0) \xrightarrow{\text{qa}} (T'; X_1) \quad (4.16)$$

is physically realizable.

Experimentally, through adiabatic expansion of gas, the system performs positive work on the surroundings, and its “temperature” decreases. See College Physics 2e §15.2 The First Law of Thermodynamics and Some Simple Processes and University Physics Volume 2 §3.6 Adiabatic Processes for an Ideal Gas, and consult in particular discussions on the “adiabatic expansion process.”

Lemma 4.1.1 (Positive Heat Transfer). *For any $(T; X_0)$, there exists X_1 with*

$$Q_{\text{max}}(T; X_0 \mapsto X_1) > 0. \quad (4.17)$$

Proof. Given $(T; X_0)$, let $(T'; X_1)$ be an adiabatic accessible lower “temperature” state as postulated in Definition 4.1.1. Consider the following isothermal cycle:

$$(T; X_1) \xrightarrow{\text{qi}} (T; X_0) \xrightarrow{\text{qa}} (T'; X_1) \xrightarrow{\text{i}} (T; X_1) \quad (4.18)$$

where the process $(T'; X_1) \xrightarrow{\text{i}} (T; X_1)$ is the generalized isothermal process under T -reservoir – not T' ! – as in Theorem 4.1.1. As stated in 10, no work is done $W_{\text{i}} = 0$. By Definition 4.1.1, we have $0 < T' < T$.

Let W_{cyc} be the work done by the above isothermal cycle under the T -reservoir. By 3.1.1, we have $W_{\text{cyc}} \leq 0$. Expanding the contributions from each process in the cycle:

$$\begin{aligned} 0 \geq W_{\text{cyc}} &= W_{\text{qi}} + W_{\text{qa}} + W_{\text{i}} \\ &= F[T; X_1] - F[T; X_0] + U(T; X_0) - U(T'; X_1) + 0 \\ &> F[T; X_1] - F[T; X_0] + U(T; X_0) - U(T(> T'); X_1) \\ &= -Q_{\text{max}}(T; X_0 \mapsto X_1), \end{aligned} \quad (4.19)$$

where we use Lemma 2.1.2 and Definition 4.0.1. ■

4.2 Carnot’s Theorem and Absolute Temperature

Let us start with a key lemma:

Lemma 4.2.1 (Tanaka’s Lemma). *Let $(T; X) \xrightarrow{\text{qi}} (T; X')$ be a quasistatic isothermal process. If $Q_{\text{max}}(T; X \mapsto X') = 0$, then there exists the corresponding quasistatic adiabatic process: $(T; X) \xrightarrow{\text{qa}} (T; X')$. In other words, an isothermal process with zero heat transfer is effectively adiabatic, where the heat bath plays no active role.*

Proof. By Lemma 2.1.1, at least either $(T; X) \xrightarrow{\text{a}} (T; X')$ or $(T; X) \xleftarrow{\text{a}} (T; X')$ exists. Suppose $(T; X) \xrightarrow{\text{a}} (T; X')$ exists; for the other case, one can interchange X and X' , see Remark 11 for this complementary part. Perform the corresponding operation $X \mapsto X'$ quasistatically:

$$(T; X) \xrightarrow{\text{qa}} (T'; X'), \quad (4.20)$$

where the final “temperature” T' is a priori unknown. We claim that T' is indeed T .

If we consider the backward quasistatic process, we have

$$(T; X) \xleftarrow{\text{qa}} (T'; X') \xrightarrow{\text{a}} (T; X) \quad (4.21)$$

By Definition 2.2.2, $T' \leq T$ holds. To show $T' = T$, suppose $T' < T$ for contradiction. By Lemma 2.1.2, we have $U(T'; X') < U(T; X')$. Now consider the following cycle:

$$(T; X) \xrightarrow{\text{qa}} (T'; X') \xrightarrow{\text{i}} (T; X') \xleftarrow{\text{qi}} (T; X) \quad (4.22)$$

where $(T'; X') \xrightarrow{\text{i}} (T; X')$ is a generalized isothermal process under the T -reservoir. The whole cycle is isothermal under the T -reservoir. Hence, by Theorem 3.1.1, the total work $W_{\text{cyc}} \leq 0$.

- Along the quasistatic adiabatic process, the work done by the process is the loss of internal energy, $U(T; X) - U(T'; X')$.
- Through the generalized isothermal process, as stated in Remark 10, the work is zero.
- By hypothesis, $Q_{\text{max}}(T; X \mapsto X') = 0$, the work done by the quasistatic isothermal process is also given by the loss of internal energy, $U(T; X') - U(T; X)$.

So, the total work done by the cycle satisfies

$$0 \geq W_{\text{cyc}} = U(T; X') - U(T; X) + 0 + U(T; X) - U(T'; X') = U(T; X') - U(T'; X'), \quad (4.23)$$

which is absurd. \blacksquare

Remark 11. If $(T; X) \xleftarrow{\text{a}} (T; X')$ exists, perform the same process quasistatically:

$$(\tilde{T}; X) \xleftarrow{\text{qa}} (T; X'). \quad (4.24)$$

By Definition 2.2.2, $T \geq \tilde{T}$ holds, since $(T; X) \xleftarrow{\text{a}} (T; X') \xleftarrow{\text{qa}} (\tilde{T}; X)$ is an adiabatic process. Suppose $T > \tilde{T}$, for contradiction. Consider the following isothermal cycle:

$$(T; X) \xrightarrow{\text{qi}} (T; X') \xrightarrow{\text{qa}} (\tilde{T}; X) \xleftarrow{\text{i}} (T; X) \quad (4.25)$$

where i-process is under the T -reservoir. By Lemma 2.1.2, $U(T; X) > U(\tilde{T}; X)$ as $T > \tilde{T}$. By Theorem 3.1.1, the total work done by this cycle is non-positive:

$$0 \geq U(T; X) - U(T; X') + U(T; X') - U(\tilde{T}; X), \quad (4.26)$$

which contrary to $U(T; X) > U(\tilde{T}; X)$. Hence, $T = \tilde{T}$.

Theorem 4.2.1 (The Universality of Q_{\max} – Carnot’s Theorem). *Let $(T_L; X_0)$ and X_1 satisfy $Q_{\max}(T_L; X_0 \mapsto X_1) > 0$, see Lemma 4.1.1. For T_H , consider $Q_{\max}(T_H; X'_0 \mapsto X'_1)$, where $(T_H; X'_0)$ and $(T_H; X'_1)$ are states such that the following quasistatic adiabatic processes exist:*

$$\begin{array}{ccc} (T_H; X'_0) & & (T_H; X'_1) \\ \uparrow qa & & \uparrow qa \\ (T_L; X_0) & & (T_L; X_1) \end{array} \quad (4.27)$$

We claim that the ratio of the maximum heat transfers, $Q_{\max}(T_L; X_0 \mapsto X_1)$ and $Q_{\max}(T_H; X'_0 \mapsto X'_1)$ depends neither on the specific systems nor on the states, but only on the “temperatures” T_L and T_H :

$$f_C(T_H, T_L) := \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)} \quad (4.28)$$

We call f_C the Carnot function.

Definition 4.2.1 (Absolute Temperature). Before proving Theorem 4.2.1, let us define absolute temperatures that we have already introduced in Remark 1 and Example 3.3.2. Observe that, for any arbitrary intermediate temperature T_M and corresponding transitions,

$$f_C(T_H, T_L) = \frac{Q_{\max}(T_H; \sim)}{Q_{\max}(T_M; \sim)} \frac{Q_{\max}(T_M; \sim)}{Q_{\max}(T_L; \sim)} = \frac{f_C(T_H, T_M)}{f_C(T_L, T_M)}, \quad (4.29)$$

where \sim stands for the corresponding transitions under the given temperatures. Since the Carnot function $f_C(T_H, T_L)$ depends only on T_H and T_L , this motivates the introduction of an absolute temperature scale such as Kelvin or Rankine, so that the Carnot function coincides with the ratio of temperatures:

$$f_C(T_H, T_L) = \frac{T_H}{T_L} = \frac{T_H/T_M}{T_L/T_M}. \quad (4.30)$$

We use an absolute temperature, instead of empirical “temperature” for equilibrium states.

Exercise 4.2.1 (Temperature Conversions). Find conversions among Celsius, Kelvin, Fahrenheit, and Rankine scales, see College Physics §13.1 Temperature and University Physics Volume 2 §1.2 Thermometers and Temperature Scales.

Let us define one of the most important concepts in Thermodynamics – the Carnot cycle.

Definition 4.2.2 (Carnot Cycle and Heat Engine). The following cycle – a heat “engine” – is called Carnot cycle:

$$\begin{array}{ccc} (T_H; X'_0) & \xrightarrow{q_i} & (T_H; X'_1) \\ \uparrow qa & & \downarrow qa \\ (T_L; X_0) & \xleftarrow{q_i} & (T_L; X_1) \end{array} \quad (4.31)$$

The work W_{cyc} done by the cycle is

$$\begin{aligned}
W_{\text{cyc}} &= W_{\text{max}}(T_{\text{H}}; X'_0 \mapsto X'_1) + U(T_{\text{H}}; X'_1) - U(T_{\text{L}}; X_1) \\
&\quad + W_{\text{max}}(T_{\text{L}}; X_1 \mapsto X_0) + U(T_{\text{L}}; X_0) - U(T_{\text{H}}; X'_0) \\
&= W_{\text{max}}(T_{\text{H}}; X'_0 \mapsto X'_1) + U(T_{\text{H}}; X'_1) - U(T_{\text{H}}; X'_0) \\
&\quad - (W_{\text{max}}(T_{\text{L}}; X_0 \mapsto X_1) + U(T_{\text{H}}; X'_0) - U(T_{\text{L}}; X_0)) \\
&= Q_{\text{max}}(T_{\text{H}}; X'_0 \mapsto X'_1) - Q_{\text{max}}(T_{\text{L}}; X_0 \mapsto X_1),
\end{aligned} \tag{4.32}$$

where we used Definition 4.0.1.

By Definition 4.0.1, $Q_{\text{max}}(T_{\text{H}}; X'_0 \mapsto X'_1)$ is the heat transfer from T_{H} -reservoir to the system. Similarly, along the process $T_1 \mapsto T_0$, the heat transfer from the T_{L} -reservoir to the system is $Q_{\text{max}}(T_{\text{H}}; X_1 \mapsto X_0) = -Q_{\text{max}}(T_{\text{H}}; X_0 \mapsto X_1) < 0$. That is, $Q_{\text{max}}(T_{\text{H}}; X_0 \mapsto X_1) > 0$ represents the heat transfer from the system to T_{L} -reservoir. This type of energy transformation – converting heat from T_{H} -reservoir into work while wasting heat $Q_{\text{max}}(T_{\text{H}}; X_0 \mapsto X_1) > 0$ to T_{L} -reservoir – is called a heat engine, see Definition 4.3.1 and University Physics Volume 2 §4.2 Heat Engines.

Proof of Theorem 4.2.1. Let Y_0 be an arbitrary state. By Lemma 4.1.1, there exists Y_1 such that $Q_{\text{max}}(T_{\text{L}}; Y_0 \mapsto Y_1) > 0$. Consider the corresponding Carnot cycle:

$$\begin{array}{ccc}
(T_{\text{H}}; Y'_0) & \xrightarrow{\text{qi}} & (T_{\text{H}}; Y'_1) \\
\text{qa} \uparrow & & \downarrow \text{qa} \\
(T_{\text{L}}; Y_0) & \xleftarrow{\text{qi}} & (T_{\text{L}}; Y_1)
\end{array} \tag{4.33}$$

Define a positive scaling parameter:

$$\lambda := \frac{Q_{\text{max}}(T_{\text{L}}; Y_0 \mapsto Y_1)}{Q_{\text{max}}(T_{\text{L}}; X_0 \mapsto X_1)} > 0. \tag{4.34}$$

Now, consider the following scaled but opposite Carnot cycle of λX together with (4.33):

$$\begin{array}{ccc}
(T_{\text{H}}; \lambda X'_1) & \xrightarrow{\text{qi}} & (T_{\text{H}}; \lambda X'_0) \\
\text{qa} \uparrow & & \downarrow \text{qa} \\
(T_{\text{L}}; \lambda X_1) & \xleftarrow{\text{qi}} & (T_{\text{L}}; \lambda X_0)
\end{array} \quad \begin{array}{ccc}
(T_{\text{H}}; Y'_0) & \xrightarrow{\text{qi}} & (T_{\text{H}}; Y'_1) \\
\text{qa} \uparrow & & \downarrow \text{qa} \\
(T_{\text{L}}; Y_0) & \xleftarrow{\text{qi}} & (T_{\text{L}}; Y_1)
\end{array} \tag{4.35}$$

They can be processed simultaneously since they share the same temperature profiles:

$$\begin{array}{ccc}
(T_{\text{H}}; \lambda X'_1 \oplus Y'_0) & \xrightarrow{\text{qi}} & (T_{\text{H}}; \lambda X'_0 \oplus Y'_1) \\
\text{qa} \uparrow & & \downarrow \text{qa} \\
(T_{\text{L}}; \lambda X_1 \oplus Y_0) & \xleftarrow{\text{qi}} & (T_{\text{L}}; \lambda X_0 \oplus Y_1)
\end{array} \tag{4.36}$$

The bottom quasistatic isothermal process satisfies

$$\begin{aligned} & Q_{\max}(T_L; \lambda X_0 \oplus Y_1 \mapsto \lambda X_1 \oplus Y_0) \\ &= \lambda Q_{\max}(T_L; X_0 \mapsto X_1) - Q_{\max}(T_L; Y_0 \mapsto Y_1) \\ &= 0, \end{aligned} \quad (4.37)$$

by the definition of the scale parameter $\lambda > 0$. Applying Lemma 4.2.1, a corresponding quasistatic adiabatic process exists. The resulting cycle is an isothermal cycle under T_H -reservoir:

$$\begin{array}{ccc} (T_H; \lambda X'_1 \oplus Y'_0) & \xrightarrow{\text{qi}} & (T_H; \lambda X'_0 \oplus Y'_1) \\ \text{qa} \uparrow & & \downarrow \text{qa} \\ (T_L; \lambda X_1 \oplus Y_0) & \xleftarrow{\text{qa}} & (T_L; \lambda X_0 \oplus Y_1) \end{array} \quad (4.38)$$

Hence, we may apply Theorem 3.1.1: the total work done is zero. Using Definition 4.2.2, we obtain

$$\begin{aligned} 0 &= -\lambda (Q_{\max}(T_H; X'_0 \mapsto X'_1) - Q_{\max}(T_L; X_0 \mapsto X_1)) \\ &\quad + Q_{\max}(T_H; Y'_0 \mapsto Y'_1) - Q_{\max}(T_L; Y_0 \mapsto Y_1) \\ &= -\frac{Q_{\max}(T_L; Y_0 \mapsto Y_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)} (Q_{\max}(T_H; X'_0 \mapsto X'_1) - Q_{\max}(T_L; X_0 \mapsto X_1)) \\ &\quad + Q_{\max}(T_H; Y'_0 \mapsto Y'_1) - Q_{\max}(T_L; Y_0 \mapsto Y_1) \\ &= -Q_{\max}(T_L; Y_0 \mapsto Y_1) \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)} + Q_{\max}(T_H; Y'_0 \mapsto Y'_1). \end{aligned} \quad (4.39)$$

Since $Q_{\max}(T_L; Y_0 \mapsto Y_1) > 0$, we obtain

$$f_C := \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)} = \frac{Q_{\max}(T_H; Y'_0 \mapsto Y'_1)}{Q_{\max}(T_L; Y_0 \mapsto Y_1)} \quad (4.40)$$

which establishes the universality of the Carnot function f_C . ■

Remark 12. See College Physics 2e §15.4 Carnot's Perfect Heat Engine: The Second Law of Thermodynamics Restated, University Physics Volume 2 §4.5 The Carnot Cycle, and June 12, 1824: Sadi Carnot publishes treatise on heat engines.¹

4.3 Efficiency of Heat Engines

Definition 4.3.1 (Efficiency of Heat Engines). Let $0 < T_L < T_H$ be two absolute temperatures. If a heat engine absorbs $Q_H > 0$ of heat from the T_H -reservoir

¹<https://www.aps.org/publications/apsnews/200906/physicshistory.cfm>

and wastes $Q_L > 0$ to the T_L -reservoir, the work W done by the engine is defined via:

$$E \begin{array}{c} \Downarrow Q_H \\ \Downarrow W \quad \Downarrow Q_L \end{array} \rightarrow E \quad W = Q_H - Q_L. \quad (4.41)$$

It is worth mentioning that the initial energy and the final energy coincide since it's a cyclic process. The efficiency ε of this heat engine is

$$\varepsilon := \frac{W}{Q_H} = 1 - \frac{Q_L}{Q_H}. \quad (4.42)$$

See College Physics §15.2 The First Law of Thermodynamics and Some Simple Processes and University Physics Volume 2 §4.2 Heat Engines.

Lemma 4.3.1 (The Efficiency of Carnot Cycle). *The efficiency of the Carnot cycle in Definition 4.2.2, if it is viewed as a heat engine, is*

$$\varepsilon_C = 1 - \frac{T_L}{T_H}, \quad (4.43)$$

where $T_L < T_H$ are the absolute temperatures of the cold and hot reservoirs.

Proof. By Definition 4.2.1, the Carnot function satisfies

$$f_C(T_H, T_L) = \frac{T_H}{T_L} = \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)} \quad (4.44)$$

and the work done in the Carnot cycle is

$$W_{\text{cyc}} = Q_{\max}(T_H; X'_0 \mapsto X'_1) - Q_{\max}(T_L; X_0 \mapsto X_1). \quad (4.45)$$

Hence, the efficiency is

$$1 - \frac{Q_{\max}(T_L; X_0 \mapsto X_1)}{Q_{\max}(T_H; X'_0 \mapsto X'_1)} = 1 - \frac{T_L}{T_H}, \quad (4.46)$$

as claimed. ■

Remark 13 (Maximum Efficiency). Carnot cycle is sometimes called a perfect heat engine: College Physics §15.4 Carnot's Perfect Heat Engine: The Second Law of Thermodynamics Restated and University Physics Volume 24.5 The Carnot Cycle. This means that for any heat engine operating between two heat baths with $T_L < T_H$, its efficiency is never greater than that of Carnot cycle.

Exercise 4.3.1. Carnot showed that no heat engine can exceed the efficiency of Carnot cycle. Let us illustrate his claim.

Consider an arbitrary heat engine:

$$e \begin{array}{c} \Downarrow q_H \\ \Downarrow w \quad \Downarrow q_L \end{array} \rightarrow e \quad (4.47)$$

1. Define the efficiency ε' of this process.

2. Let $\lambda := \frac{q_H}{Q_H}$ and consider the inverse of the λ -scaled Carnot cycle as in Lemma 4.3.1.
3. Combine these two processes – the engine (4.47) and the scaled inverse Carnot process in Lemma 4.3.1 – to form a new heat engine:

$$E' \begin{array}{c} \xrightarrow{\Downarrow Q'_H} \\ \Downarrow W' \quad \Downarrow Q'_L \end{array} E' \quad (4.48)$$

Determine W' , Q'_H , and Q'_L .

4. Show that the combined system thermally interacts with only one heat bath.
5. If we identify such a cycle as an isothermal process. Then, by Theorem 3.1.1, conclude $\varepsilon' \leq \varepsilon_C$.

Carnot's theorem can be proved under milder assumptions with full mathematical rigor, see Theorem 5.3.1.

Chapter 5

Entropy

Heat cannot be completely converted to mechanical work; there is always some inevitable loss. The thermodynamic quantity that provides an analytical expression of loss of availability is called entropy.

5.1 Entropy

Definition 5.1.1 (Entropy). For an equilibrium state $(T; X)$, we define the entropy S by

$$S(T; X) := \frac{U(T; X) - F[T; X]}{T}. \quad (5.1)$$

For a quasistatic isothermal process, $(T; X_1) \xrightarrow{\text{qi}} (T; X_2)$, recalling Definition 4.0.1, the heat transfer $Q_{\max}(T; X_1 \mapsto X_2)$ from T -reservoir is

$$Q_{\max}(T; X_1 \mapsto X_2) = U(T; X_2) - F[T; X_2] - (U(T; X_1) - F[T; X_1]) \quad (5.2)$$

Hence, entropy S satisfies, along $(T; X_1) \xrightarrow{\text{qi}} (T; X_2)$,

$$S(T; X_1) \xrightarrow{\Downarrow Q_{\max}/T} S(T; X_2) \quad S(T; X_2) - S(T; X_1) = \frac{Q_{\max}(T; X_1 \mapsto X_2)}{T} \quad (5.3)$$

See also College Physics §15.6 Entropy and the Second Law of Thermodynamics and University Physics Volume 2 §4.6 Entropy. The entropy $S(T; X)$ is a stock, and the corresponding flow is the maximum heat transfer per temperature.

Remark 14 (Availability and Unavailability). Recalling the natures of Helmholtz free energy F and internal energy U , the very definition of entropy $S := \frac{U-F}{T}$ implies the following:

When entropy increases, a certain amount of energy becomes permanently unavailable to do work. The energy is not lost, but its character is changed, so that some of it can never be converted to

doing work—that is, to an organized force acting through a distance.¹

Exercise 5.1.1. Determine the corresponding SI unit for the entropy S . See NIST Guide to the SI, Chapter 4: The Two Classes of SI Units and the SI Prefixes².

Lemma 5.1.1. *Under the quasistatic adiabatic processes in Theorem 4.2.1:*

$$\begin{array}{ccc} (T_H; X'_0) & & (T_H; X'_1) \\ \uparrow \text{ } qa & & \uparrow \text{ } qa \\ (T_L; X_0) & & (T_L; X_1) \end{array} \quad (5.4)$$

the change in entropy is invariant:

$$S(T_H; X'_0) - S(T_L; X_0) = S(T_H; X'_1) - S(T_L; X_1). \quad (5.5)$$

Proof. By Theorem 4.2.1 and Definition 4.2.1, for the given quasistatic adiabatic processes, the Carnot function satisfies

$$\frac{T_H}{T_L} = \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{Q_{\max}(T_L; X_0 \mapsto X_1)}. \quad (5.6)$$

Hence, using Definition 5.1.1, we have

$$\begin{aligned} S(T_H; X'_1) - S(T_H; X'_0) &= \frac{Q_{\max}(T_H; X'_0 \mapsto X'_1)}{T_H} \\ &= \frac{Q_{\max}(T_L; X_0 \mapsto X_1)}{T_L} \\ &= S(T_L; X_1) - S(T_L; X_0). \end{aligned} \quad (5.7)$$

This proves the invariance of entropy change under quasistatic adiabatic processes. ■

Remark 15 (Entropy and Quasistatic Adiabatic Process). As we did for internal energy in Definition 2.1.3 and Helmholtz free energy in Definition 3.2.2, we may choose a reference point so that the entropy itself is invariant under quasistatic adiabatic processes. Let $(T_*; \lambda X_*)$ be such a reference point for $\lambda > 0$. We assign the corresponding entropy value λS_* for a scaled system:

$$S(T_*; \lambda X_*) := \lambda S_*. \quad (5.8)$$

Then, for any state $(T; \lambda X)$ and a quasistatic adiabatic process $(T; \lambda X) \xleftrightarrow{qa} (T_*; \lambda X_*)$,

$$S(T; \lambda X) := \lambda S_*. \quad (5.9)$$

¹College Physics 2e §15.6 Entropy and the Second Law of Thermodynamics: Disorder and the Unavailability of Energy

²Chapter 4 of <https://www.nist.gov/pml/special-publication-811>

In particular, if we choose $(T_L; X_0)$ as the reference point $(T_*; X_*)$, we obtain $0 = S(T_H; X'_1) - S(T_L; X_1)$. That is, along a quasistatic adiabatic process, say $(T_L; X_1) \xrightarrow{\text{qa}} (T_H; X'_1)$, entropy remains constant:

$$S(T_L; X_1) = S(T_H; X'_1). \quad (5.10)$$

Theorem 5.1.1. *For a fixed system X , its entropy S is an increasing function of the temperature. Moreover, for a state $(T; X)$, if both entropy S and internal energy are differentiable at $(T; X)$:*

$$\frac{1}{T} \frac{\partial U(T; X)}{\partial T} = \frac{\partial S(T; X)}{\partial T}. \quad (5.11)$$

Remark 16 (The Heat Capacity). Recalling Definition 2.1.4, we have

$$C_V(T; X) = T \frac{\partial S(T; X)}{\partial T}. \quad (5.12)$$

Proof. Let $0 < T_1 < T_2$. For an arbitrary state X_1 state, select states X_2, X_3 satisfying:

$$(T_2; X_1) \xleftrightarrow{\text{qa}} (T_1; X_2), (T_1; X_1) \xleftrightarrow{\text{qa}} (T_2; X_3). \quad (5.13)$$

Consider the following two cycles:

$$\begin{array}{ccc} (T_2; X_1) & & (T_2; X_1) \xrightarrow{\text{qi}} (T_2; X_3) \\ \uparrow \text{qa} & \searrow \text{i}' & \downarrow \text{qa} \\ (T_1; X_2) & \xleftarrow{\text{qi}} (T_1; X_1) & (T_1; X_1) \end{array} \quad (5.14)$$

- Left cycle

The process $(T_2; X_1) \xrightarrow{\text{i}'} (T_1; X_1)$ is a T_1 -isothermal process with no work, see Remark 10. Since the entire cycle is under the T_1 -reservoir, by Theorem 3.1.1, the total work satisfies

$$\begin{aligned} 0 &\geq W_{\max}(T_1; X_1 \mapsto X_2) + W_{\text{ad}}\left((T_1; X_2) \xrightarrow{\text{qa}} (T_2; X_2)\right) + 0 \\ &= F[T_1; X_1] - F[T_1; X_2] + U(T_1; X_2) - U(T_2; X_1) \\ &\quad - U(T_1; X_1) + U(T_1; X_1) \\ &= T_1(S(T_1; X_2) - S(T_1; X_1)) - U(T_2; X_1) + U(T_1; X_1) \end{aligned} \quad (5.15)$$

As stated in Remark 15, the entropy is invariant under quasistatic adiabatic processes, $S(T_1; X_2) = S(T_2; X_1)$. Hence,

$$T_1(S(T_2; X_1) - S(T_1; X_1)) - U(T_2; X_1) + U(T_1; X_1) \leq 0. \quad (5.16)$$

Arranging, we obtain

$$S(T_2; X_1) - S(T_1; X_1) \leq \frac{U(T_2; X_1) - U(T_1; X_1)}{T_1}. \quad (5.17)$$

- Right cycle

Along the right cycle, since it is an isothermal cycle under the T_2 -reservoir, the total work satisfies:

$$\begin{aligned}
0 &\geq W_{\max}(T_2; X_1 \mapsto X_3) + W_{\text{ad}}\left((T_2; X_3) \xrightarrow{\text{qa}} (T_1; X_1)\right) + 0 \\
&= F[T_2; X_1] - F[T_2; X_3] + U(T_2; X_3) - U(T_1; X_1) \\
&\quad - U(T_2; X_1) + U(T_2; X_1) \\
&= T_2(S(T_2; X_3) - S(T_2; X_1)) - U(T_1; X_1) + U(T_2; X_1) \\
&= T_2(S(T_1; X_1) - S(T_2; X_1)) - U(T_1; X_1) + U(T_2; X_1),
\end{aligned} \tag{5.18}$$

since $S(T_1; X_1) = S(T_2; X_3)$. Hence, we obtain

$$\frac{U(T_2; X_1) - U(T_1; X_1)}{T_2} \leq S(T_2; X_1) - S(T_1; X_1). \tag{5.19}$$

By Lemma 2.1.2, U is an increasing function of temperature. Thus, the left-hand side is positive since $0 < T_1 < T_2$, and we conclude that the entropy is also an increasing function of temperature:

$$S(T_1; X_1) < S(T_2; X_1). \tag{5.20}$$

Combining the outcomes, we obtain

$$\frac{1}{T_2} \frac{U(T_2; X_1) - U(T_1; X_1)}{T_2 - T_1} \leq \frac{S(T_2; X_1) - S(T_1; X_1)}{T_2 - T_1} \leq \frac{1}{T_1} \frac{U(T_2; X_1) - U(T_1; X_1)}{T_2 - T_1} \tag{5.21}$$

Taking the limit $T_2 \rightarrow T_1$, we obtain the desired result. \blacksquare

Corollary 5.1.1.1. *As chosen above, if two states are accessible with a quasistatic adiabatic process, say $(T_1; X_1) \xleftrightarrow{\text{qa}} (T_2; X_2)$, then $S(T_1; X_1) = S(T_2; X_2)$ holds. Conversely, if $S(T_1; X_1) = S(T_2; X_2)$, then there exists a quasistatic adiabatic process connecting these two states.*

Proof. Suppose $S(T_1; X_1) = S(T_2; X_2)$. Starting from the state $(T_1; X_1)$, consider the following quasistatic adiabatic process:

$$(T_1; X_1) \xrightarrow{\text{qa}} (T_3; X_2), \tag{5.22}$$

where T_3 is the final temperature by this adiabatic process. We will show that $T_3 = T_2$.

Because it is a quasistatic adiabatic process, the entropy remains constant, $S(T_1; X_1) = S(T_3; X_2)$. Hence, $S(T_2; X_2) = S(T_3; X_2)$. As shown in Theorem 5.1.1, the entropy for fixed X_2 state is increasing function of temperature. Hence, the equality $S(T_2; X_2) = S(T_3; X_2)$ implies $T_2 = T_3$. \blacksquare

Example 5.1.1 (Entropy and Helmholtz Free Energy of Ideal Gas). Let us examine the constant $v(T)$ that appeared in (3.46) of Example 3.3.2. Consider a state $\left(T; \left(\frac{V}{N}\right)\right)$ with a reference point:

$$\begin{aligned} \left(T; \lambda \left(\frac{V}{N}\right)\right) &\xleftrightarrow{\text{qa}} \left(T; \lambda \left(\frac{V_*}{N}\right)\right). \\ S\left(T_*; \lambda \left(\frac{V_*}{N}\right)\right) &:= \lambda cNR, \lambda > 0. \end{aligned} \quad (5.23)$$

As shown in Example 3.3.2, we have U and F for the ideal gas. Hence,

$$S\left(T; \left(\frac{V}{N}\right)\right) := \frac{U\left(T; \left(\frac{V}{N}\right)\right) - F\left[T; \left(\frac{V}{N}\right)\right]}{T} = \frac{cNRT + Nu + NRT \ln \frac{V}{v(T)N}}{T} \quad (5.24)$$

The entropy remains constant under a quasistatic adiabatic process, as shown in Remark 15. Thus, we have

$$\lambda \left(\frac{Nu}{T} + NR \ln \frac{V}{v(T)N} \right) = 0, \lambda > 0. \quad (5.25)$$

Taking the exponential, we obtain

$$v(T) = \frac{V}{N} \exp\left(\frac{u}{RT}\right). \quad (5.26)$$

Recalling Example 3.3.2, the Poisson relation for an ideal gas is $T^c V = T_*^c V_*$:

$$V = \left(\frac{T_*}{T}\right)^c V_*, \quad (5.27)$$

we establish:

$$v(T) = \left(\frac{T_*}{T}\right)^c \frac{V_*}{N} \exp\left(\frac{u}{RT}\right) = \left(\frac{T_*}{T}\right)^c v_* \exp\left(\frac{u}{RT}\right). \quad (5.28)$$

Substituting back, we obtain the entropy for an ideal gas:

$$\begin{aligned} S\left(T; \lambda \left(\frac{V}{N}\right)\right) &= \lambda \left(cNR + NR \ln \left(\left(\frac{T}{T_*}\right)^c \frac{V}{V_*} \right) \right) \\ &= \lambda \left(cNR + NR \ln \left(\left(\frac{T}{T_*}\right)^c \frac{V}{v_* N} \right) \right). \end{aligned} \quad (5.29)$$

We also have

$$F\left[T; \left(\frac{V}{N}\right)\right] = -NRT \ln \frac{V}{v(T)N} = -NRT \ln \left(\left(\frac{T}{T_*}\right)^c \frac{V}{V_*} \right) + Nu. \quad (5.30)$$

Example 5.1.2 (Ideal Gas Thermometer). Recalling Example 5.1.1, let us examine an ideal gas as a thermometer. The Helmholtz free energy of an ideal gas is

$$F \left[T; \left(\frac{V}{N} \right) \right] = -NRT \ln \left(\left(\frac{T}{T_*} \right)^c \frac{V}{V_*} \right) + Nu, \quad (5.31)$$

where T is an absolute temperature in Definition 4.2.1. We will see that T in the state equation (3.42) of Example 3.3.2 is indeed the absolute temperature. Consider the following Carnot cycle with constant N :

$$\begin{array}{ccc} (T_H; V'_0) & \xrightarrow{\text{qi}} & (T_H; V'_1) \\ \text{qa} \uparrow & & \downarrow \text{qa} \\ (T_L; V_0) & \xleftarrow{\text{qi}} & (T_L; V_1) \end{array} \quad (5.32)$$

As shown in Example 3.3.2, under quasistatic isothermal processes, the internal energy does not change. Hence, we have

$$\begin{aligned} f_C(T_H, T_L) &:= \frac{Q_{\max}(T_H; V'_0 \mapsto V'_1)}{Q_{\max}(T_L; V_0 \mapsto V_1)} \\ &= \frac{F \left[T_H; \left(\frac{V'_0}{N} \right) \right] - F \left[T_H; \left(\frac{V'_1}{N} \right) \right] + U \left(T_H; \left(\frac{V'_1}{N} \right) \right) - U \left(T_H; \left(\frac{V'_0}{N} \right) \right)}{F \left[T_L; \left(\frac{V_0}{N} \right) \right] - F \left[T_L; \left(\frac{V_1}{N} \right) \right] + F \left[T_L; \left(\frac{V_1}{N} \right) \right] - F \left[T_L; \left(\frac{V_0}{N} \right) \right]} \\ &= \frac{F \left[T_H; \left(\frac{V'_0}{N} \right) \right] - F \left[T_H; \left(\frac{V'_1}{N} \right) \right]}{F \left[T_L; \left(\frac{V_0}{N} \right) \right] - F \left[T_L; \left(\frac{V_1}{N} \right) \right]} \\ &= \frac{NRT_H \ln \left(\frac{V'_1}{V'_0} \right)}{NRT_L \ln \left(\frac{V_1}{V_0} \right)} \end{aligned} \quad (5.33)$$

Poisson equation in Example 3.3.2 implies:

$$\begin{aligned} (T_H)^c V'_1 &= (T_L)^c V_1 \\ (T_H)^c V'_0 &= (T_L)^c V_0. \end{aligned} \quad (5.34)$$

Taking the ratio, we have $\frac{V'_1}{V'_0} = \frac{V_1}{V_0}$. Substituting this back, we obtain

$$f_C(T_H, T_L) = \frac{T_H}{T_L}. \quad (5.35)$$

Thus, the temperature in the ideal gas state equation $pV = NRT$ is the absolute temperature.

Example 5.1.3 (Entropy and Heat). Along a quasistatic isothermal process $(T; X) \xrightarrow{\text{qi}} (T; X')$ define

$$\begin{aligned}\Delta Q &:= Q_{\max}(T; X \mapsto X') \\ \Delta S &:= S(T; X') - S(T; X).\end{aligned}\tag{5.36}$$

Then, by Definition 5.1.1, (5.3) gives

$$\Delta S = \frac{\Delta Q}{T}.\tag{5.37}$$

If $X \mapsto X'$ is quasistatic and adiabatic, then no heat transfers, $\Delta Q = 0$, and hence $\Delta S = 0$, see Remark 15. Thus, both sides are zero.

From (T, X) to (T', X') , consider the following sequence of quasistatic isothermal and quasistatic adiabatic processes:

$$(T, X) \xrightarrow{\text{qi}} (T; X_1) \xrightarrow{\text{qa}} (T_1, X_1) \xrightarrow{\text{qi}} (T_1; X_2) \xrightarrow{\text{qa}} (T_2, X_2) \xrightarrow{\text{qi}} \cdots (T', X')\tag{5.38}$$

Such a path from $(T; X)$ to $(T'; X')$ is not unique, but along any specific path, we can collect the entropy change:

$$S(T'; X') - S(T; X) = \sum_{k=1}^n \Delta S_k = \sum_{k=1}^n \frac{\Delta Q_k}{T_k},\tag{5.39}$$

where $(T_n; X_n) = (T'; X')$, $(T_0; X_0) = (T; X)$, and

$$\Delta Q_k = \Delta Q_k + 0 = Q_{\max}(T_{k-1}; X_{k-1} \mapsto X_k) + 0\tag{5.40}$$

is the net heat transfer to the system along $(T_{k-1}, X_{k-1}) \xrightarrow{\text{qi}} (T_{k-1}; X_k) \xrightarrow{\text{qa}} (T_k, X_k)$ for $k \in \{1, \dots, n\}$. If we formally take the limit $n \rightarrow \infty$, we obtain the Riemann integral representation of the entropy difference:

$$S(T'; X') - S(T; X) = \int_{(T; X)}^{(T'; X')} \frac{dQ}{T}.\tag{5.41}$$

The integral in right-hand side depends explicitly on the path but, in our formalism, the left-hand side depends only on the initial state and the final state. See University Physics Volume 2 §4.6 Entropy.

5.2 Entropy Principle

Theorem 5.2.1 (Entropy Principle). *Let X_1, X_2 be physically accessible states. For $T_1, T_2 > 0$, an adiabatic process $(T_1; X_1) \xrightarrow{a} (T_2; X_2)$ exists iff $S(T_1; X_1) \leq S(T_2; X_2)$.*

Remark 17. As a consequence, an adiabatic process from $(T_1; X_1)$ to $(T_2; X_2)$ is reversible iff $S(T_1; X_1) = S(T_2; X_2)$. Since any quasistatic process is reversible by Definition 2.1.1 and Corollary 5.1.1.1, the entropy remains constant under quasistatic processes.

Proof. (\Rightarrow) Suppose an adiabatic process $(T_1; X_1) \xrightarrow{a} (T_2; X_2)$ exists. Perform the backward operation $X_2 \mapsto X_1$ quasistatically and adiabatically:

$$(T_1; X_1) \xleftrightarrow{qa} (T_3; X_2), \quad (5.42)$$

where T_3 of the resulting temperature is, a priori, unknown. Since quasistatic adiabatic processes preserve entropy, $S(T_1; X_1) = S(T_3; X_2)$. If we combine these two processes, we have

$$(T_2; X_2) \xrightarrow{a} (T_1; X_1) \xleftrightarrow{qa} (T_3; X_2). \quad (5.43)$$

By Definition 2.2.2, $T_2 \leq T_3$ holds. Since the entropy of X_2 an increasing function of temperature, $S(T_2; X_2) \leq S(T_3; X_2) = S(T_1; X_1)$.

(\Leftarrow) Conversely, suppose $S(T_1; X_1) \leq S(T_2; X_2)$. Along $X_1 \mapsto X_2$, consider the following quasistatic adiabatic process:

$$(T_1; X_1) \xrightarrow{qa} (T_4; X_2), \quad (5.44)$$

where T_4 is unknown. Since a quasistatic adiabatic process preserves entropy, we have

$$S(T_4; X_2) = S(T_1; X_1) \leq S(T_2; X_2). \quad (5.45)$$

It follows $T_4 \leq T_2$ since entropy is an increasing function of temperature. By Definition 2.1.2, $(T_4; X_2) \xrightarrow{a} (T_2; X_2)$ exists. Hence, we obtain the desired adiabatic process $(T_1; X_1) \xrightarrow{qa} (T_4; X_2) \xrightarrow{a} (T_2; X_2)$. \blacksquare

Theorem 5.2.2 (Entropy is Essentially Unique). *Let $\lambda > 0$. Suppose S' satisfies the entropy principle in Theorem 5.2.1, and*

$$\begin{aligned} S'(T; \lambda X_1) &= \lambda S'(T; X_1) \\ S'(T; X_1 \oplus X_2) &= S'(T; X_1) + S'(T; X_2), \end{aligned} \quad (5.46)$$

for any X_1, X_2 and T . Then, there exist constants $\alpha > 0$ and β such that

$$S'(T; \lambda X_3) = \alpha S(T; \lambda X_3) + \lambda \beta \quad (5.47)$$

for any state $(T; X_3)$. In other words, the entropy is unique up to an affine transformation with a positive scale.

Proof. Let $T > 0$, and X_1, X_2 be two physically accessible states of some system. Suppose $(T; X_1)$ and $(T; X_2)$ have different entropy, without loss of generality, $S(T; X_1) < S(T; X_2)$. By Theorem 5.2.1, an adiabatic process $(T; X_1) \xrightarrow{a} (T; X_2)$ and, hence, $S'(T; X_1) < S'(T; X_2)$. Define

$$\alpha := \frac{S'(T; \lambda X_2) - S'(T; \lambda X_1)}{S(T; \lambda X_2) - S(T; \lambda X_1)} \quad (5.48)$$

and

$$\beta := S'(T; X_1) - \alpha S(T; X_1). \quad (5.49)$$

Then $S'(T; X_1) = \alpha S(T; X_1)$ and $S'(T; X_2) = \alpha S(T; X_2)$.

Let X_3 be an accessible state from X_1 . Consider $(T; X_3)$.

- $S(T; X_3) \leq S(T; X_1)$ case

Define

$$\lambda := \frac{S(T; X_1) - S(T; X_3)}{S(T; X_2) - S(T; X_1)}. \quad (5.50)$$

Rearranging yields

$$S(T; (\lambda + 1)X_1) = S(T; \lambda X_2 \oplus X_3). \quad (5.51)$$

i.e., $(T; (\lambda + 1)X_1) \xleftrightarrow{\text{qa}} (T; \lambda X_2 \oplus X_3)$ exists. Applying S' , we obtain $(\lambda + 1)S'(T; X_1) = \lambda S'(T; X_2) + S'(T; X_3)$. Solving this equation for λ , we obtain

$$\frac{S(T; X_1) - S(T; X_3)}{S(T; X_2) - S(T; X_1)} = \lambda = \frac{\alpha S(T; X_1) + \beta - S'(T; X_3)}{\alpha (S(T; X_2) - S(T; X_1))} \quad (5.52)$$

- $S(T; X_3) > S(T; X_1)$ case

Define

$$\lambda := \frac{S(T; X_3) - S(T; X_1)}{S(T; X_2) - S(T; X_1)}. \quad (5.53)$$

We, then, obtain $S(T; X_1 \oplus \lambda X_2) = S(T; \lambda X_1 \oplus X_3)$, i.e., $(T; X_1 \oplus \lambda X_2) \xleftrightarrow{\text{qa}} (T; \lambda X_1 \oplus X_3)$ exists. Applying S' and rearranging, we obtain

$$\frac{S(T; X_3) - S(T; X_1)}{S(T; X_2) - S(T; X_1)} = \lambda = \frac{S'(T; X_3) - \alpha S(T; X_1) - \beta}{\alpha (S(T; X_2) - S(T; X_1))}. \quad (5.54)$$

Hence, we conclude $S'(T; X_3) = \alpha S(T; X_3) + \beta$. ■

5.3 Entropy for Composite System

Definition 5.3.1. For a composite system

$$\{(T_1; X_1) | \cdots | (T_n; X_n)\} \quad (5.55)$$

where $|$ denotes an adiabatic wall as in Lemma 3.0.1, we define

$$S(\{(T_1; X_1) | \cdots | (T_n; X_n)\}) := \sum_{j=1}^n S(T_j; X_j). \quad (5.56)$$

Lemma 5.3.1 (Entropy Principle for Composite System). *Suppose (X_1, \dots, X_n) and (X'_1, \dots, X'_m) are physically accessible. Then an adiabatic process*

$$(\{(T_1; X_1) | \cdots | (T_n; X_n)\}) \xrightarrow{a} (\{(T'_1; X'_1) | \cdots | (T'_m; X'_m)\}) \quad (5.57)$$

exists iff

$$S(\{(T_1; X_1) | \cdots | (T_n; X_n)\}) \leq S(\{(T'_1; X'_1) | \cdots | (T'_m; X'_m)\}). \quad (5.58)$$

Proof. It suffices to consider the binary case, $n = 2 = m$, $\{(T_1; X_1) | (T_2; X_2)\}$. Its entropy is

$$S(T_1; X_1) + S(T_2; X_2). \quad (5.59)$$

Fix the value $S(T_2; X_2)$. We may adjust the temperature of the second component to T_1 by choosing an accessible state \widetilde{X}_2 such that

$$S(T_2; X_2) = S(T_1; \widetilde{X}_2). \quad (5.60)$$

By Theorem 5.2.1, there exists a quasistatic adiabatic process:

$$(T_2; X_2) \xleftrightarrow{\text{qa}} (T_1; \widetilde{X}_2). \quad (5.61)$$

Thus, we have

$$\{(T_1; X_1) | (T_2; X_2)\} \xleftrightarrow{\text{qa}} \{(T_1; X_1) | (T_1; \widetilde{X}_2)\} \xleftrightarrow{\text{qa}} (T_1; X_1 \oplus \widetilde{X}_2) \quad (5.62)$$

where the final step is the adiabatic wall removal. Since the total system is already at T_1 , the wall removal can be done quasistatically and adiabatically. Similarly,

$$\{(T'_1; X'_1) | (T'_2; X'_2)\} \xleftrightarrow{\text{qa}} \{(T'_1; X'_1) | (T'_1; \widetilde{X}'_2)\} \xleftrightarrow{\text{qa}} (T'_1; X'_1 \oplus \widetilde{X}'_2). \quad (5.63)$$

Therefore, $(\{(T_1; X_1) | (T_2; X_2)\} \xrightarrow{\text{a}} (\{(T'_1; X'_1) | (T'_2; X'_2)\})$ exists iff

$$(T_1; X_1 \oplus \widetilde{X}_2) \xrightarrow{\text{a}} (T'_1; X_1 \oplus \widetilde{X}_2) \quad (5.64)$$

exists. Since we can apply 5.2.1, namely the entropy principle for a single system, $(\{(T_1; X_1) | (T_2; X_2)\} \xrightarrow{\text{a}} (\{(T'_1; X'_1) | (T'_2; X'_2)\})$ exists iff

$$S(T_1; X_1 \oplus \widetilde{X}_2) \leq S(T'_1; X_1 \oplus \widetilde{X}_2), \quad (5.65)$$

where $S(T_1; X_1 \oplus \widetilde{X}_2) = S(T_1; X_1) + S(T_2; X_2)$ and $S(T'_1; X_1 \oplus \widetilde{X}_2) = S(T'_1; X'_1) + S(T'_2; X'_2)$. ■

Remark 18. Repeating this process for all components, we obtain

$$S(\{(T_1; X_1) | \cdots | (T_n; X_n)\}) = S(T_1; X_1 \oplus \widetilde{X}_2 \oplus \cdots \oplus \widetilde{X}_n) \quad (5.66)$$

and similarly,

$$S(\{(T'_1; X'_1) | \cdots | (T'_m; X'_m)\}) = S(T'_1; X'_1 \oplus \widetilde{X}'_2 \oplus \cdots \oplus \widetilde{X}'_m) \quad (5.67)$$

That is, an adiabatic process

$$(T_1; X_1 \oplus \widetilde{X}_2 \oplus \cdots \oplus \widetilde{X}_n) \xrightarrow{\text{a}} (T'_1; X'_1 \oplus \widetilde{X}'_2 \oplus \cdots \oplus \widetilde{X}'_m) \quad (5.68)$$

exists iff the following inequality is the case:

$$S(T_1; X_1 \oplus \widetilde{X}_2 \oplus \cdots \oplus \widetilde{X}_n) \leq S(T'_1; X'_1 \oplus \widetilde{X}'_2 \oplus \cdots \oplus \widetilde{X}'_m). \quad (5.69)$$

Since quasistatic adiabatic processes are reversible, we obtain the desired result, namely,

$$S(\{(T_1; X_1) | \cdots | (T_n; X_n)\}) \leq S(\{(T'_1; X'_1) | \cdots | (T'_m; X'_m)\}) \quad (5.70)$$

iff the following adiabatic process exists:

$$\begin{array}{ccc} (\{(T_1; X_1) | \cdots | (T_n; X_n)\}) & & (\{(T'_1; X'_1) | \cdots | (T'_m; X'_m)\}) \\ \text{qa} \downarrow & & \uparrow \text{qa} \\ (T_1; X_1 \oplus \widetilde{X}_2 \oplus \cdots \oplus \widetilde{X}_n) & \xrightarrow{a} & (T'_1; X'_1 \oplus \widetilde{X}'_2 \oplus \cdots \oplus \widetilde{X}'_m) \end{array} \quad (5.71)$$

As discussed in Remark 13 and Exercise 4.3.1, Carnot cycles achieve the maximum possible efficiency among all heat engines. We now present a more rigorous formulation of this result, following [LY99].

Theorem 5.3.1 (Maximum Efficiency (Carnot)). *Under the hypothesis of Theorem 5.1.1 for an arbitrary temperature and state, no heat engine can operate with greater efficiency than a Carnot cycle.*

Proof. Consider a heat engine, a cyclic process around $(T; X)$. Its efficiency is $1 - \frac{Q_L}{Q_H}$, corresponding to the following diagram:

$$U(T; X) \begin{array}{c} \xrightarrow{\Downarrow Q_H} \\ \Downarrow W \quad \Downarrow Q_L \end{array} U(T; X) \quad W = Q_H - Q_L. \quad (5.72)$$

Let $(T_L; L)$ and $(T_H; H)$ be two finite heat baths, with initial temperatures $0 < T_L < T_H$. During one cycle, the transition of the composite system is represented as

$$((T_H; H)|(T; X)|(T_L; L)) \xrightarrow{a} ((T'_H; H)|(T; X)|(T'_L; L)). \quad (5.73)$$

The cold T_L -reservoir absorbs

$$Q_L := U(T'_L; L) - U(T_L; L) \quad (5.74)$$

of heat from the cycle, while the hot T_H -reservoir supplies

$$Q_H := U(T_H; H) - U(T'_H; H). \quad (5.75)$$

Diagrammatically, we have

$$\begin{array}{ccc}
U(T_H; H) & \cdots \cdots \cdots \rightarrow & U(T_H'; H) \\
& \downarrow Q_H & \\
U(T; X) & \cdots \cdots \cdots \rightarrow & U(T; X) \\
& \downarrow W & \\
U(T_L; L) & \cdots \cdots \cdots \rightarrow & U(T_L'; L) \\
& \downarrow Q_L &
\end{array} \quad W = Q_H - Q_L. \quad (5.76)$$

Assume $Q_H > 0$ and $Q_L > 0$. Then, by Lemma 2.1.2,

$$T_L < T_L', T_H' < T_H. \quad (5.77)$$

By Lemma 5.3.1, during this cycle,

$$S((T_H; H)|(T; X)|(T_L; L)) \leq S((T_H'; H)|(T; X)|(T_L'; L)). \quad (5.78)$$

Using Definition 5.3.1, we obtain

$$S(T_H; H) + S(T_L; L) \leq S(T_H'; H) + S(T_L'; L). \quad (5.79)$$

Rearranging yields

$$S(T_H; H) - S(T_H'; H) \leq S(T_L'; L) - S(T_L; L) \quad (5.80)$$

If $T \mapsto S(T; H)$ is differentiable in some neighborhood of $T_H' \leq T \leq T_H$, the left-hand side becomes

$$\begin{aligned}
S(T_H; H) - S(T_H'; H) &= \int_{T_H'}^{T_H} \frac{\partial S(T; H)}{\partial T} dT \\
&= \int_{T_H'}^{T_H} \frac{1}{T} \frac{\partial U(T; H)}{\partial T} dT \\
&\geq \frac{1}{T_H} \int_{T_H'}^{T_H} \frac{\partial U(T; H)}{\partial T} dT \\
&= \frac{1}{T_H} (U(T_H; H) - U(T_H'; H)) \\
&= \frac{Q_H}{T_H}.
\end{aligned} \quad (5.81)$$

Similarly, if $T \mapsto S(T; L)$ is differentiable in some neighborhood of $T_L' \leq T \leq$

T_L , left-hand side becomes

$$\begin{aligned}
S(T_L; L) - S(T_L'; L) &= \int_{T_L}^{T_L'} \frac{\partial S(T; L)}{\partial T} dT \\
&= \int_{T_L}^{T_L'} \frac{1}{T} \frac{\partial U(T; L)}{\partial T} dT \\
&\leq \frac{1}{T_L} \int_{T_L}^{T_L'} \frac{\partial U(T; L)}{\partial T} dT \\
&= \frac{1}{T_L} (U(T_L'; L) - U(T_L; L)) \\
&= \frac{Q_L}{T_L}.
\end{aligned} \tag{5.82}$$

Thus, we obtain $\frac{Q_H}{T_H} \leq \frac{Q_L}{T_L}$, or equivalently,

$$1 - \frac{Q_L}{Q_H} \leq 1 - \frac{T_L}{T_H}. \tag{5.83}$$

The right-hand side $1 - \frac{T_L}{T_H}$ is the efficiency of Carnot cycle with two heat baths $T_L < T_H$. ■

Definition 5.3.2 (Thermal Contact and Equilibrium). Consider the wall removal process in Lemma 3.0.1 with $\lambda = 1$:

$$((T; X)|(T'; Y)) \xrightarrow{a} (\tilde{T}; X \oplus Y) \tag{5.84}$$

Let Q denote the heat transfer from Y to X :

$$Q = U(\tilde{T}; X) - U(T; X) = U(T'; Y) - U(\tilde{T}; Y). \tag{5.85}$$

If $Q = 0$, these two systems are said to be in thermal equilibrium, written

$$(T; X) \sim (T'; Y) \tag{5.86}$$

meaning that, under the process (5.84), no heat transfer occurs between X and Y .

Theorem 5.3.2 (Thermal Contact and Equilibrium). *For the adiabatic wall removal process in (5.84), the following statements hold:*

- If the heat transfer between X and Y is zero, then $T = \tilde{T} = T'$.
- If $T \neq T'$, then entropy of the composite system increases.
- If $(T; X) \sim (T'; Y)$ and $(T'; Y) \sim (T''; Z)$, then $(T; X) \sim (T''; Z)$.

Proof. Assume first that the heat transfer in (5.84) is zero. By Definition 5.3.2,

$$U(\tilde{T}; X) - U(T; X) = 0 = U(T'; Y) - U(\tilde{T}; Y). \quad (5.87)$$

By Lemma 2.1.2, both differences vanish only when $T = \tilde{T} = T'$.

Now assume $T \neq T'$. Then heat transfer must occur. Let

$$Q = U(\tilde{T}; X) - U(T; X) = U(T'; Y) - U(\tilde{T}; Y) \quad (5.88)$$

be the heat transfer from Y to X . Without loss of generality, we may suppose $Q > 0$, otherwise, interchange $X \leftrightarrow Y$. Lemma 2.1.2 implies

$$T < \tilde{T} < T'. \quad (5.89)$$

The entropy change is

$$\begin{aligned} \Delta S &:= S(\tilde{T}; X \oplus Y) - S(T; X) - S(T'; Y) \\ &= S(\tilde{T}; X) - S(T; X) - S(T'; Y) + S(\tilde{T}; Y) \\ &= \int_T^{\tilde{T}} \frac{\partial S(t; X)}{\partial t} dt - \int_{\tilde{T}}^{T'} \frac{\partial S(t; Y)}{\partial t} dt \end{aligned} \quad (5.90)$$

By Theorem 5.1.1, we obtain:

$$\begin{aligned} \Delta S &= \int_T^{\tilde{T}} \frac{1}{t} \frac{\partial U(t; X)}{\partial t} dt - \int_{\tilde{T}}^{T'} \frac{1}{t} \frac{\partial U(t; Y)}{\partial t} dt \\ &> \frac{1}{\tilde{T}} \int_T^{\tilde{T}} \frac{\partial U(t; X)}{\partial t} dt - \frac{1}{\tilde{T}} \int_{\tilde{T}}^{T'} \frac{\partial U(t; Y)}{\partial t} dt \\ &= \frac{1}{\tilde{T}} \left(U(\tilde{T}; X) - U(T; X) - U(T'; Y) + U(\tilde{T}; Y) \right) \end{aligned} \quad (5.91)$$

Since the process is adiabatic and no net work is done, the last expression is zero, $U(T; X) + U(T'; Y) = U(\tilde{T}; X \oplus Y)$. Therefore,

$$\Delta S > 0. \quad (5.92)$$

Remark 19 (Second Law of Thermodynamics). This is the Clausius form of the second law of thermodynamics: a spontaneous heat transfer occurs only from higher to lower temperature.

The word “spontaneously” here means no other effort has been made by a third party, or one that is neither the hotter nor colder object.³

See also College Physics §15.6 Entropy and the Second Law of Thermodynamics and University Physics Volume 2 §4.6 Entropy.

³University Physics Volume 2 §4.1 Reversible and Irreversible Processes

Finally, suppose X and Y are in thermal equilibrium, and Y and Z are in thermal equilibrium as well. As shown above, we have $T = T' = T''$. Consider the following wall removal:

$$((T; X)|(T; Z)) \xrightarrow{a} (\tilde{T}; X \oplus Z). \quad (5.93)$$

The heat transfer $Q_{X \leftarrow Z}$ from Z to X is

$$Q_{X \leftarrow Z} = U(\tilde{T}; X) - U(T; X) = U(T; Z) - U(\tilde{T}; Z). \quad (5.94)$$

If $T < \tilde{T}$, by Lemma 2.1.2, we have

$$\begin{aligned} U(\tilde{T}; X) - U(T; X) &> 0 \\ U(T; Z) - U(\tilde{T}; Z) &< 0, \end{aligned} \quad (5.95)$$

which is absurd; if $\tilde{T} < T$, the signs reverse, we have, again, a contradiction:

$$\begin{aligned} U(\tilde{T}; X) - U(T; X) &< 0 \\ U(T; Z) - U(\tilde{T}; Z) &> 0, \end{aligned} \quad (5.96)$$

Thus, $T = \tilde{T}$, so $Q_{X \leftarrow Z} = 0$ holds. ■

Remark 20 (Zeroth Law of Thermodynamics). The final property is known as the zeroth law of thermodynamics. From a mathematical perspective, the relation of thermal equilibrium defines an equivalence relation on the set of thermodynamic states:

- Reflexivity
For any state $(T; X)$, we have $(T; X) \sim (T; X)$.
- Symmetry
If $(T; X) \sim (T'; Y)$, then $(T'; Y) \sim (T; X)$.
- Transitivity
If $(T; X) \sim (T'; Y)$ and $(T'; Y) \sim (T''; Z)$, then $(T; X) \sim (T''; Z)$.

For further discussion, see College Physics 2e §13.1 Temperature and University Physics Volume 2 §1.1 Temperature and Thermal Equilibrium.

5.4 Applications

Theorem 5.4.1 (Helmholtz Free Energy is a Complete Thermodynamic Function). *Suppose Helmholtz free energy is differentiable at $(T; X)$. Then*

$$\begin{aligned} S(T; X) &= -\frac{\partial F[T; X]}{\partial T} \\ U(T; X) &= -T^2 \frac{\partial}{\partial T} \left(\frac{F[T; X]}{T} \right) \end{aligned} \quad (5.97)$$

That is, if F is known as a function of states, $[T; X]$, both the entropy S and the internal energy U can be obtained from it. Hence, as a function of $[T; X]$, F is sometimes called a complete thermodynamic function.

Remark 21 (The Heat Capacity). Recalling Definition 2.1.4 and Remark 16, we obtain

$$C_V(T; X) = -T \frac{\partial^2 F[T; X]}{\partial T^2}. \quad (5.98)$$

Proof. By Definition 5.1.1 and Theorem 5.1.1,

$$\begin{aligned} \frac{\partial F[T; X]}{\partial T} &= \frac{\partial (U(T; X) - TS(T; X))}{\partial T} \\ &= \frac{\partial U(T; X)}{\partial T} - S(T; X) - T \frac{\partial S(T; X)}{\partial T} \\ &= -S(T; X). \end{aligned} \quad (5.99)$$

Similarly,

$$\begin{aligned} -T^2 \frac{\partial}{\partial T} \left(\frac{F[T; X]}{T} \right) &= -T^2 \frac{\partial}{\partial T} \left(\frac{U(T; X)}{T} - S(T; X) \right) \\ &= -T^2 \left(\frac{1}{T} \frac{\partial U(T; X)}{\partial T} - \frac{U(T; X)}{T^2} - \frac{\partial S(T; X)}{\partial T} \right) \\ &= U(T; X) + T \left(T \frac{\partial S(T; X)}{\partial T} - \frac{\partial U(T; X)}{\partial T} \right) \\ &= U(T; X). \end{aligned} \quad (5.100)$$

■

Definition 5.4.1 (Chemical Potential of Fluid). As in Example 1.2.1 and Example 3.3.1, consider a $\left(T; \begin{pmatrix} V \\ N \end{pmatrix}\right)$ with a variation of the particle number $N \mapsto N + \Delta N$. We define the chemical potential μ by

$$\mu \left(T; \begin{pmatrix} V \\ N \end{pmatrix} \right) := \frac{\partial F \left[T; \begin{pmatrix} V \\ N \end{pmatrix} \right]}{\partial N}. \quad (5.101)$$

Example 5.4.1 (The Chemical Potential of Ideal Gas). Using the expression for F in Example 5.1.1, the chemical potential of an ideal gas is computed as follows:

$$\begin{aligned} \mu \left(T; \begin{pmatrix} V \\ N \end{pmatrix} \right) &= \frac{\partial}{\partial N} \left(-NRT \ln \left(\left(\frac{T}{T_*} \right)^c \frac{V}{v_* N} \right) + Nu \right) \\ &= RT - RT \ln \left(\left(\frac{T}{T_*} \right)^c \frac{V}{v_* N} \right) + u \end{aligned} \quad (5.102)$$

Example 5.4.2 (Maxwell's Relations – Energy Equation and Ideal Gas). For simplicity, consider a fluid in the state $\left(T; \left(\frac{V}{N}\right)\right)$. Assume F is sufficiently smooth, in particular twice continuously differentiable. Then the following derivatives commute:

$$\frac{\partial}{\partial V} \frac{\partial F \left[T; \left(\frac{V}{N}\right) \right]}{\partial T} = \frac{\partial}{\partial T} \frac{\partial F \left[T; \left(\frac{V}{N}\right) \right]}{\partial V} \quad (5.103)$$

Using Theorem 5.4.1 and (3.38), we obtain the Maxwell relation

$$\frac{\partial S \left(T; \left(\frac{V}{N}\right) \right)}{\partial V} = \frac{\partial p \left(T; \left(\frac{V}{N}\right) \right)}{\partial T}. \quad (5.104)$$

Since $U = TS + F$ by Definition 5.1.1, the differentiation with respect to V yields the following equation:

$$\begin{aligned} \frac{\partial U \left(T; \left(\frac{V}{N}\right) \right)}{\partial V} &= \frac{\partial}{\partial V} \left(TS \left(T; \left(\frac{V}{N}\right) \right) + F \left[T; \left(\frac{V}{N}\right) \right] \right) \\ &= T \frac{\partial p \left(T; \left(\frac{V}{N}\right) \right)}{\partial T} - p \left(T; \left(\frac{V}{N}\right) \right) \end{aligned} \quad (5.105)$$

If we apply this energy equation to the state equation $p = \frac{NRT}{V}$ of an ideal gas, see Example 3.3.2, we obtain

$$\frac{\partial U \left(T; \left(\frac{V}{N}\right) \right)}{\partial V} = T \frac{\partial p \left(T; \left(\frac{V}{N}\right) \right)}{\partial T} - p \left(T; \left(\frac{V}{N}\right) \right) = T \frac{\partial}{\partial T} \left(\frac{NRT}{V} \right) - \frac{NRT}{V} = 0 \quad (5.106)$$

Thus, the internal energy of an ideal gas does not depend on the volume – Joule's law, see Example 3.3.3

Example 5.4.3 (Adiabatic Expansion). Consider an adiabatic expansion of the fluid $\left(\frac{V}{N}\right)$ from Example 1.2.1. Let the volume increase $V \mapsto V + \Delta V$ by $\Delta V > 0$:

$$\left(T; \left(\frac{V}{N}\right) \right) \xrightarrow{a} \left(T'; \left(\frac{V + \Delta V}{N}\right) \right), \quad (5.107)$$

where T' is the final temperature. We claim that

$$S \left(T; \left(\frac{V}{N}\right) \right) < S \left(T'; \left(\frac{V + \Delta V}{N}\right) \right). \quad (5.108)$$

To show this, consider the following quasistatic adiabatic compression

$$\left(T'; \left(\frac{V + \Delta V}{N}\right)\right) \xrightarrow{\text{qa}} \left(T''; \left(\frac{V}{N}\right)\right) \quad (5.109)$$

which returns the system to its original volume, where T'' is a priori unknown. Since the pressure of the fluid is always positive during this compression, positive work is done on the system:

$$U(T'; V + \Delta V, N) \xrightarrow{\Downarrow W_{\text{external}} > 0} U(T''; V, N) \quad (5.110)$$

Combining this with the above adiabatic expansion, we have

$$U(T; V, N) \xrightarrow{\Downarrow W_{\text{external}} > 0} U(T''; V, N) \quad U\left(T; \left(\frac{V}{N}\right)\right) + W = U\left(T''; \left(\frac{V}{N}\right)\right), \quad (5.111)$$

so that $U(T''; V, N) - U(T; V, N) = W > 0$. Hence,

$$U(T; V, N) < U(T''; V, N). \quad (5.112)$$

By Lemma 2.1.2, this implies $T < T''$. Then, by Theorem 5.1.1,

$$S\left(T; \left(\frac{V}{N}\right)\right) < S\left(T''; \left(\frac{V}{N}\right)\right) = S\left(T'; \left(\frac{V + \Delta V}{N}\right)\right). \quad (5.113)$$

Thus, such an adiabatic expansion is irreversible, by Theorem 5.2.1. See University Physics Volume 2 §4.7 Entropy on a Microscopic Scale.

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