Teaching Entropy with Fun

Regina Rüffler, Georg Job

FOUNDATION

c/o. Institute of Physical Chemistry,

University of Hamburg

ChemEd Conference 2017

Brookings / USA, July 2017

Outline

1. Introduction—Entropy
2. Macroscopic Properties of Entropy
3. Entropy Transfer
4. Measuring Entropy
5. Applying the Concept of Entropy
6. Outlook

1. Introduction—Entropy

Introduction

The benefit of chemical thermodynamics is beyond question but the field is reputed to be difficult to learn. One of its most important fundamental quantities, *entropy S*, commonly introduced by an abstract mathematical expression

$$S(p,T) = S_0 + \int_{p_0,T_0}^{p,T} \frac{\mathrm{d}Q_{\mathrm{rev}}}{T}$$

which involves heat and temperature, seems especially hard to grasp.

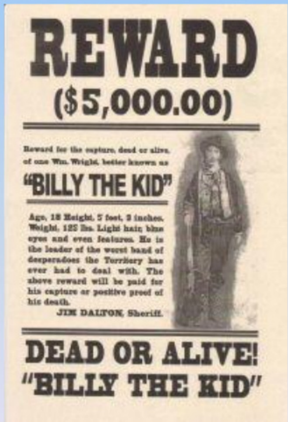
Therefore, it could be regarded as a kind of "black sheep" of the thermodynamic quantities.

Entropy as Basic Concept

However, there is a simpler and faster way to an understanding of this quantity that does not make use of higher mathematics.

$$\cancel{S(p,T) = S_0 + \int_{p_0,T_0}^{p,T} \frac{dQ_{rev}}{T}}$$

We propose to introduce *entropy S* as an in matter distributed, more or less mobile entity which is at first characterized by its typical and easily observable properties, i.e. by designing a kind of "wanted poster."



This *phenomenological definition* is followed by a direct measuring procedure, a method usual for various basic quantities such as length, time and mass.

Application

The proposed approach is elementary, does not require any special previous knowledge and immediately leads to results which can be utilized practically. This allows to start teaching the subject even at introductory high school level.

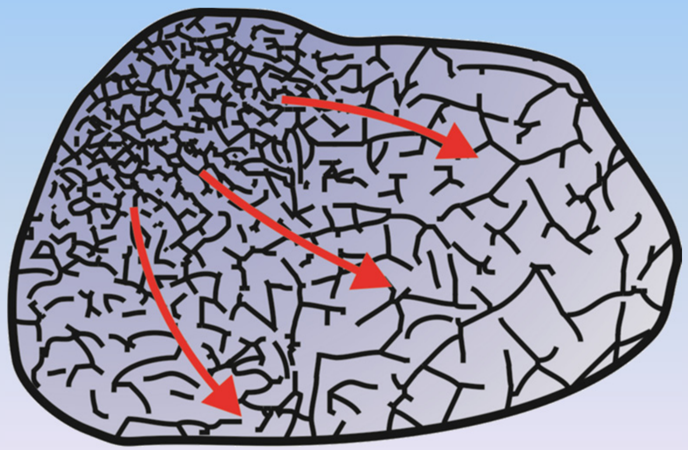
More than fourteen illustrative but nevertheless simple and safe demonstration experiments to this topic contribute essentially to deepen comprehension and forge links with everyday experiences.

2. Macroscopic Properties of Entropy

"Wanted Poster" of Entropy

Entropy can be visualized as

- **an in matter distributed,**
- **more or less mobile weightless entity**
- **with the special characteristic to be generable but not destroyable.**



These assumptions allow us to describe entropy as a substance-like (extensive) quantity which can be taught in an analogous manner as the electrical charge.

"Wanted Poster" of Entropy

Entropy changes the state of an object noticeably.

If matter contains little entropy, it is felt to be *cold*.

If the same object contains more or a lot of entropy, it feel warm or even *hot*.

If the amount of entropy in it is continously increased,

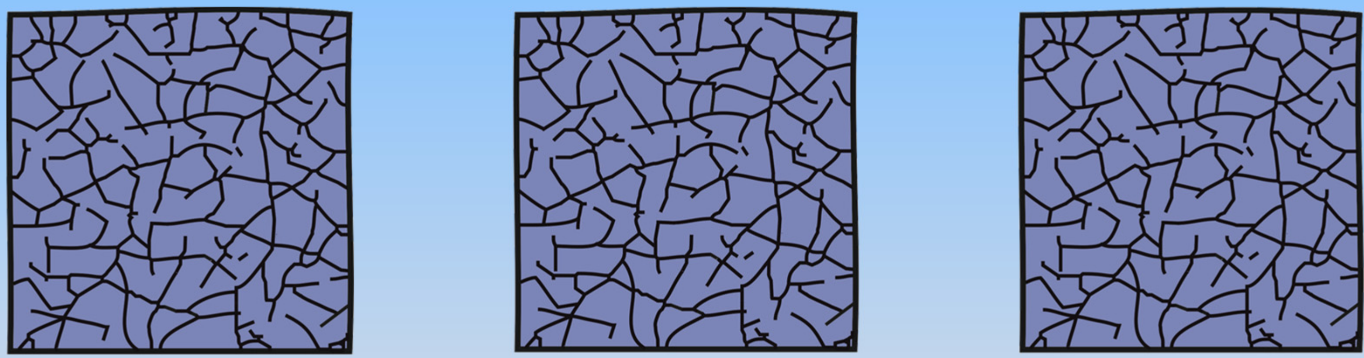
- **it will begin to glow,**
- **subsequently melt,**
- **and finally vaporize.**

Entropy plays a role in all thermal effects and can be considered their actual cause.

"Wanted Poster" of Entropy

1. **Each object contains more or less entropy.**

   Identical objects in the same state contain equal amounts of entropy.

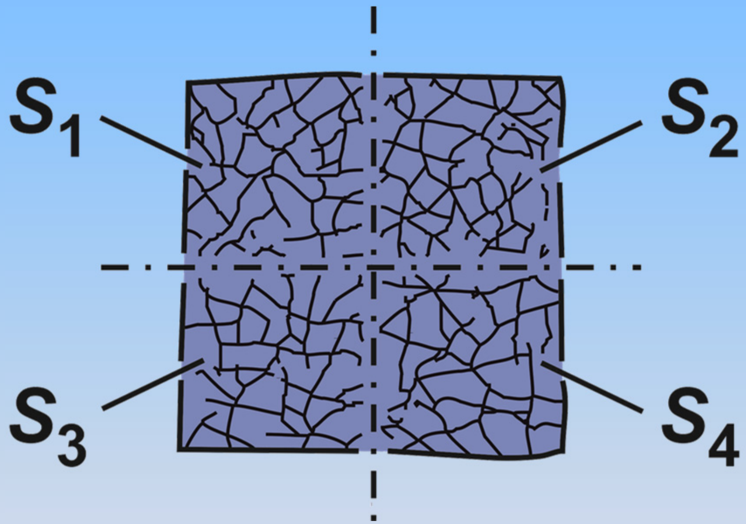


$$S_1 = S_2 = S_3$$

in other words:
"Entropy is a *state quantity*."

"Wanted Poster" of Entropy

2. **The entropy contained in a composite object is the sum of the entropies of its parts.**

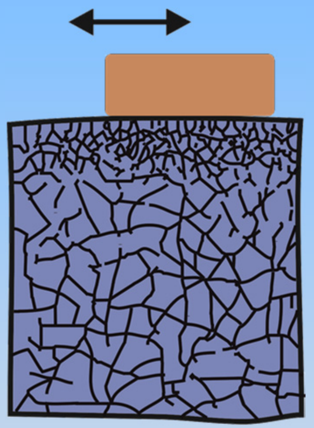


$$S_{total} = S_1 + S_2 + S_3 + S_4$$

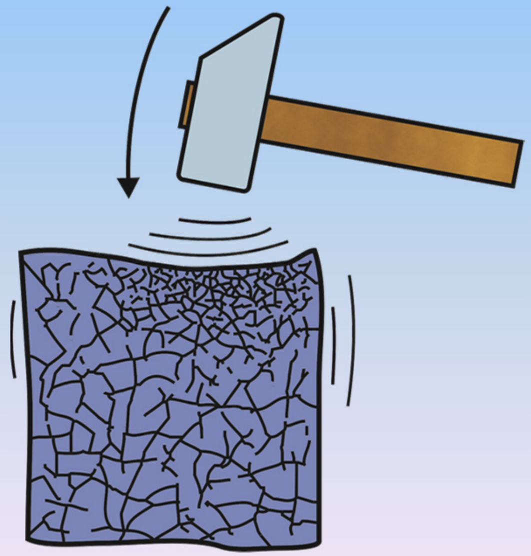
in other words:
"Entropy is an *extensive (substance-like) quantity*."

"Wanted Poster" of Entropy

3. Entropy can be *generated* by nearly all kinds of processes *but* not *destroyed*.



Friction

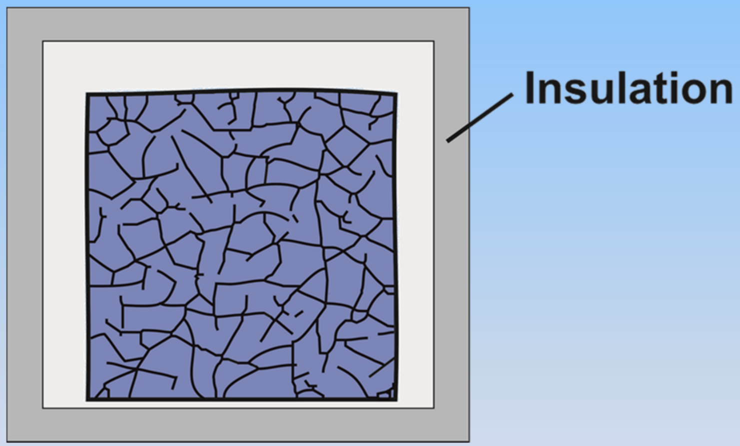


Forging

"Wanted Poster" of Entropy

4. **Entropy can<u>not</u> penetrate thermally insulating walls.**

To sum up: The amount of entropy in an insulated system can only increase but never decrease; at best its amount remains constant.



$$\Delta S \geq 0$$

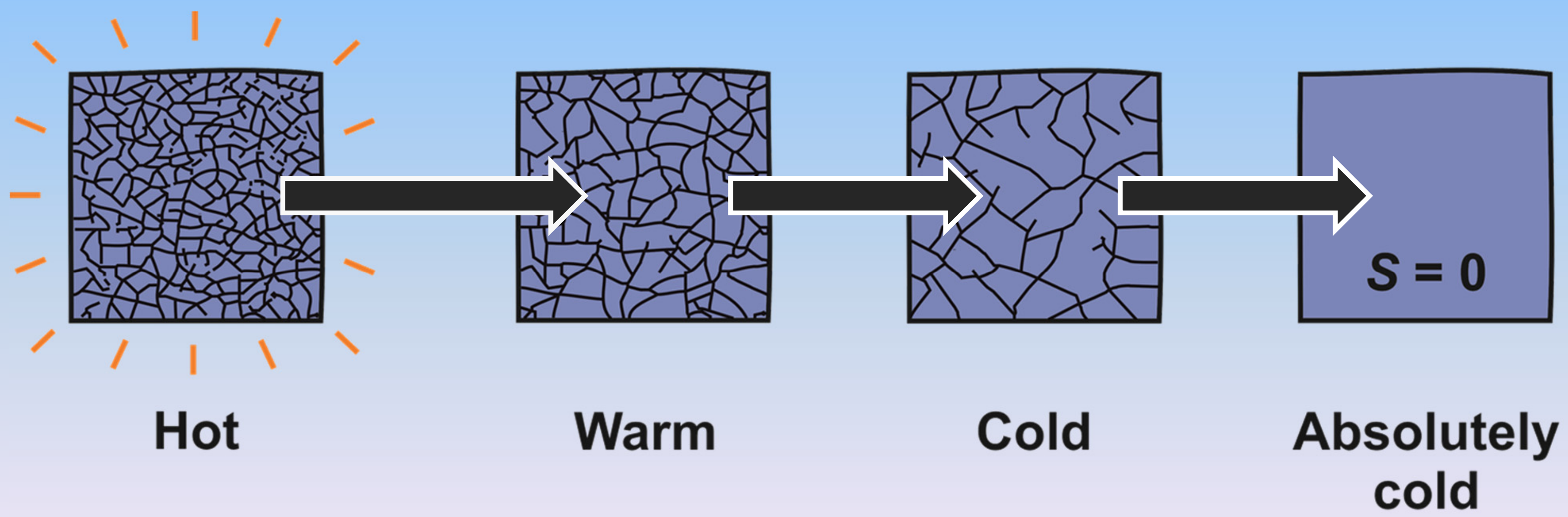
also known as

"*2nd law of thermodynamics*"

"Wanted Poster" of Entropy

5. The *main effect* of increasing entropy is that the matter becomes *warmer* (see forging experiment).

   Of two otherwise identical objects, the one with more entropy is the warmer one. An object with no entropy is absolutely cold.



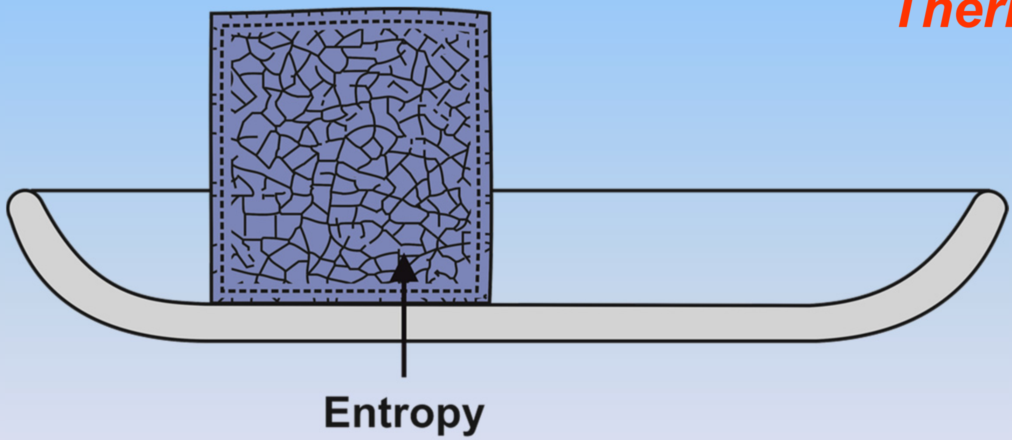
Entropy flows spontaneously from a warmer to a colder object.

"Wanted Poster" of Entropy

6. **An increase of entropy can also cause numerous *side effects*.**

   One of the most important is a *change in volume*: Usually, the object *expands*.

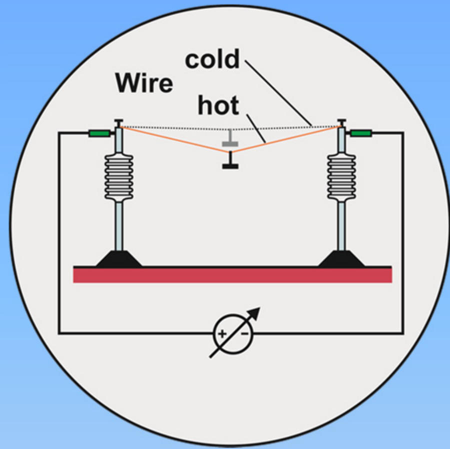
Thermal expansion

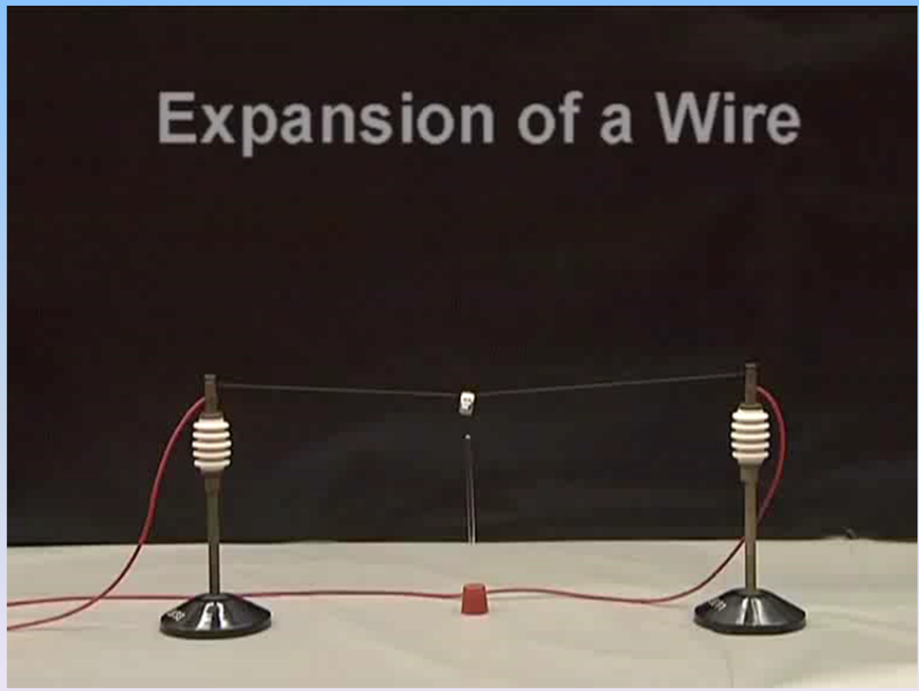


Expansion by Electric Current

Procedure:

First, the current is slowly increased. Then, the current is decreased again.

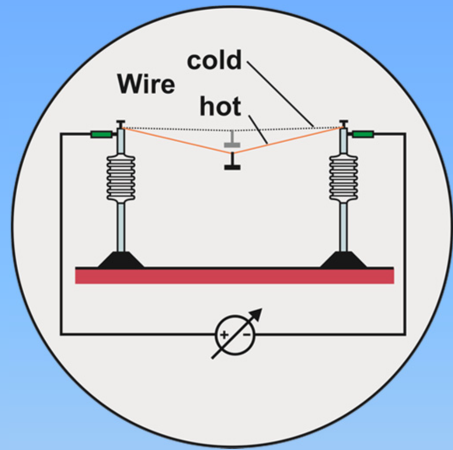




Expansion by Electric Current

Procedure:

First, the current is slowly increased. Then, the current is decreased again.



Observation:

The weight sinks slowly down with increasing current. At higher current, the wire also begins to glow. If the current is decreased the weight moves upwards again.

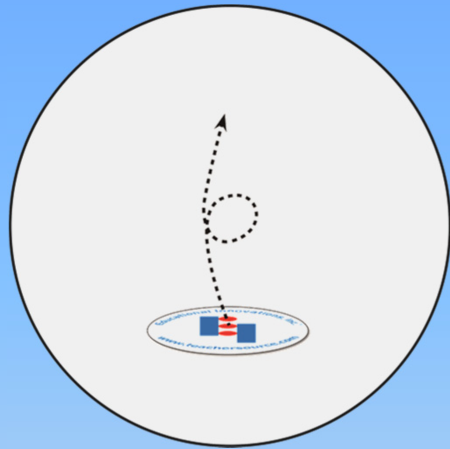
Explanation:

Entropy is generated by the electric current. As *main effect* of the increase in entropy the wire becomes warmer and finally begins to glow. But the increasing entropy also causes a *side effect*: The wire lengthens noticeably. If the electric current is decreased again, also the entropy generated in the wire decreases; the wire gradually cools down and shrinks again.

Jumping Disc

Procedure:

The disc is warmed and then “clicked” into the “inverted” shape. Subsequently, the disc is placed on the table.



Observation:

After a short while, the disc suddenly snaps back into its original shape with a loud click and jumps into the air.

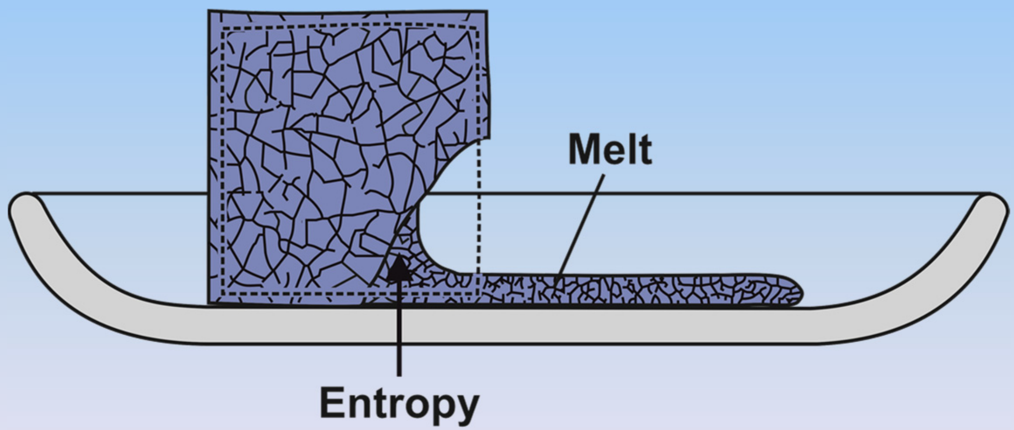
Explanation:

The disc consists of two layers of different metals (so-called “bi-metal”). When the entropy of the disc is increased, the two metals expand differently and above a temperature of approx. 310 K the disc stays in the “inverted” position. When the disc cools down, the metals shrink again and the disc returns spontaneously to its original shape. The jumping disc works on the same principle as a thermostat.

"Wanted Poster" of Entropy

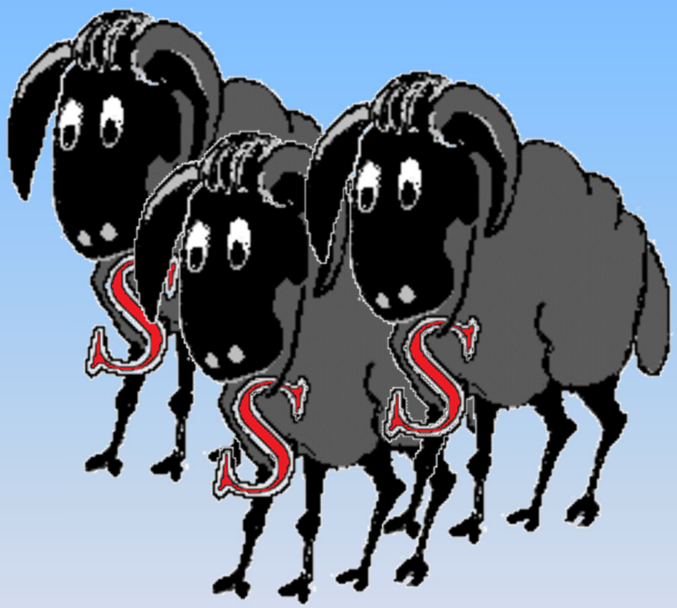
7. **If the entropy is continously increased, the substance will finally *melt* (*change in state of aggregation*).**

   At melting temperature, the entropy still flowing in will accumulate in the melt. Therefore, the liquid contains more entropy than the solid.



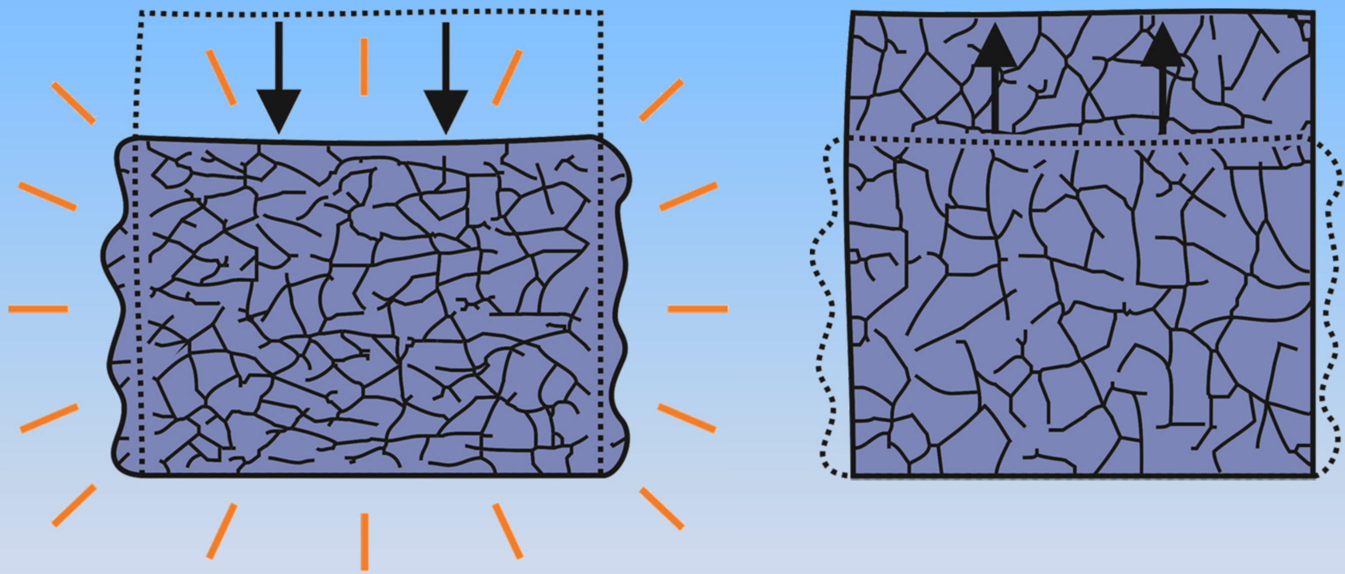
If a substance changes completely from solid to liquid state at its melting point, the entropy inside it increases by a *given* amount.

3. Entropy Transfer



Entropy and Volume

Every object expanding on heating becomes warmer on compression and colder when it expands (LE CHATELIER's principle).

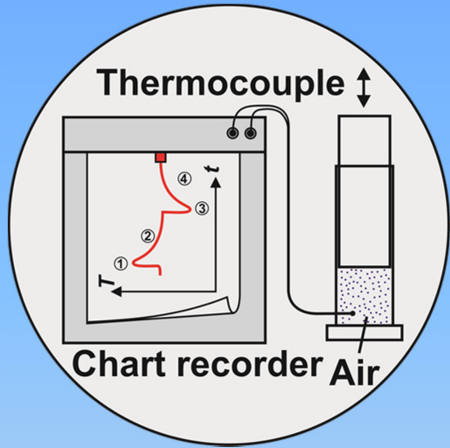


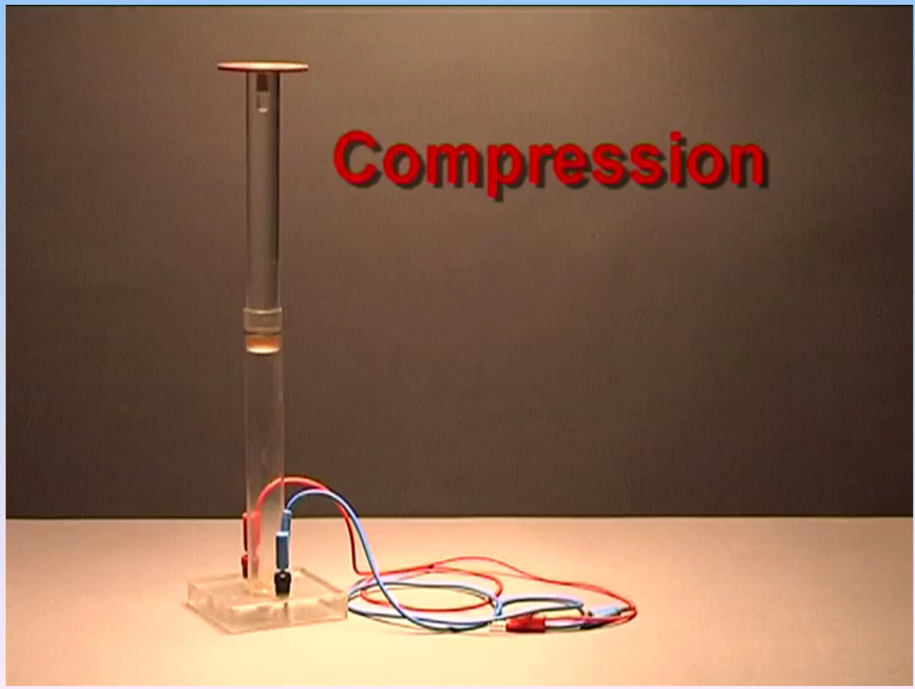
These compression and expansion effects can be especially well observed in substances that can be easily compressed such as gases.

Compression and Expansion of Air

Procedure:

Air is rapidly compressed with a piston in a cylinder having a thermocouple built in. The piston is held down until the pen has returned to its original position and then the piston is released.

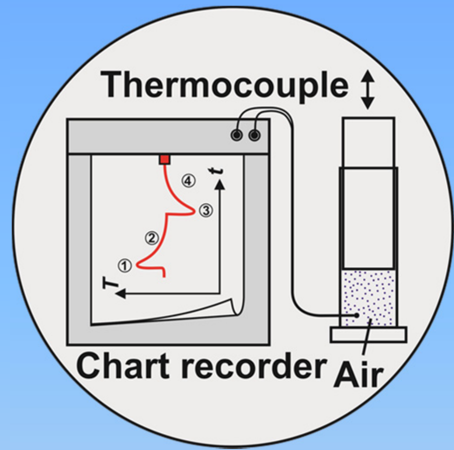




Compression and Expansion of Air

Procedure:

Air is rapidly compressed with a piston in a cylinder having a thermocouple built in. The piston is held down until the pen has returned to its original position and then the piston is released.



Observation and Explanation:

If air is compressed the gas becomes warmer (phase 1).

After a while, the gas cools down because it is not insulated from the cylinder walls and the entropy can flow out of the system into the environment (phase 2).

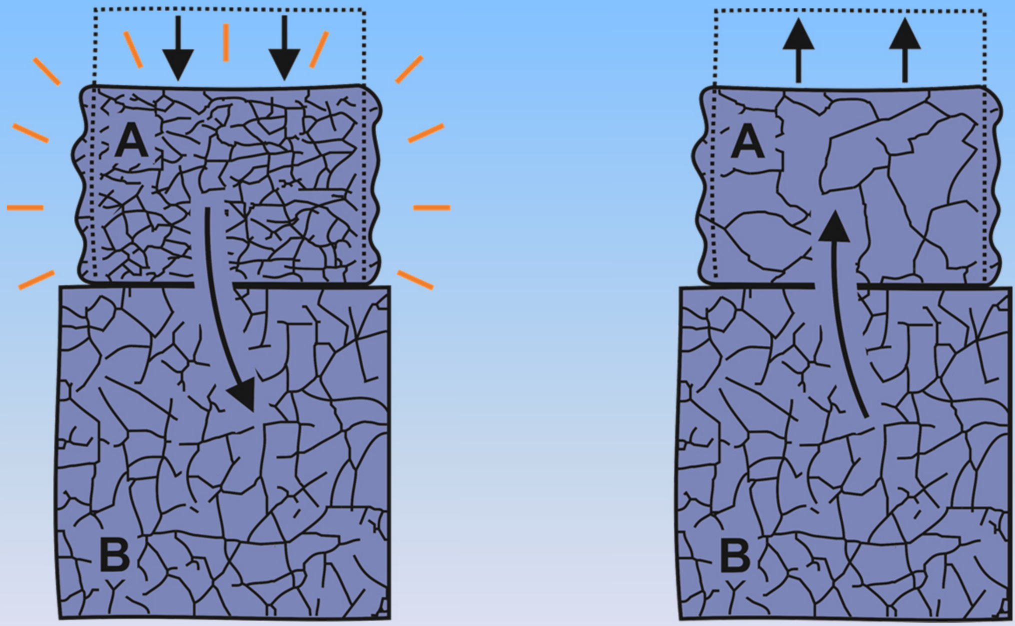
The piston´s expansion leads to a further cooling (phase 3).

Then, entropy begins to flow back and the gas starts to warm up again (phase 4).

Directed Exchange of Entropy

An object A in contact with an object B which is as warm as A releases entropy into B on compression …

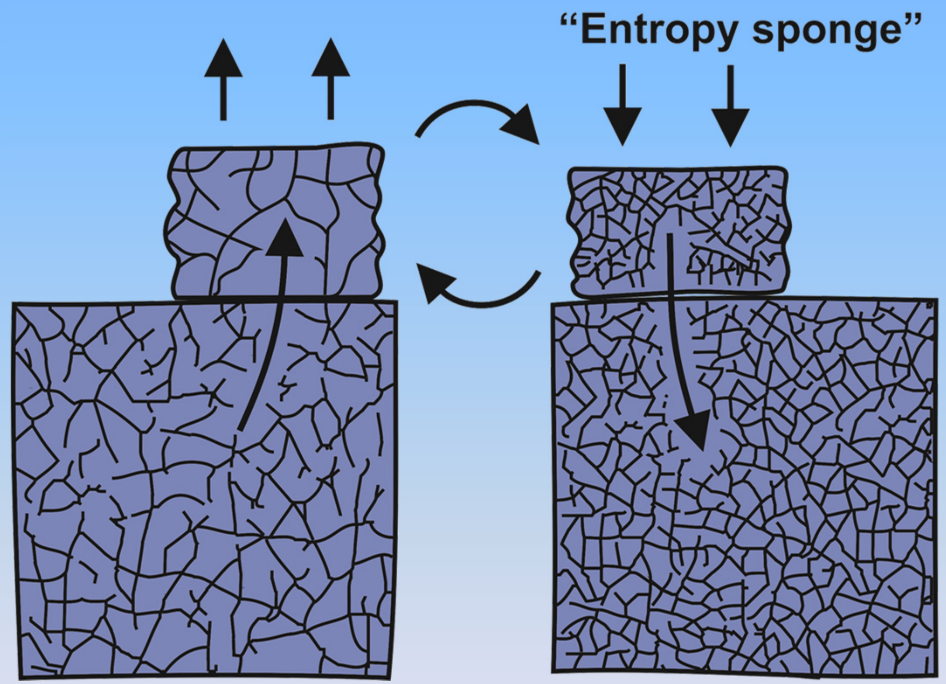
and takes entropy up on expansion.



Therefore, the object A can be regarded as a kind of "entropy sponge."

Entropy Transfer

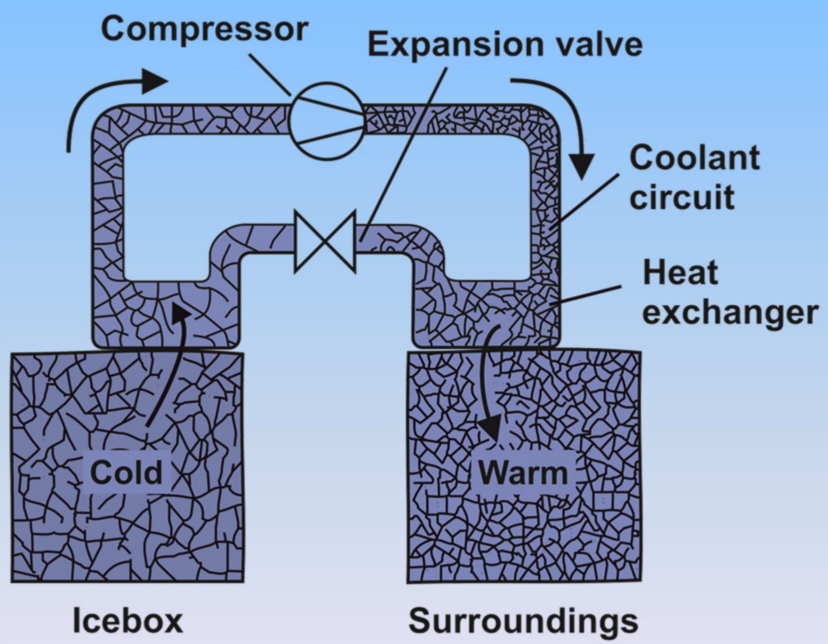
Such an "entropy sponge" can be used to transfer entropy from a cold to a hot object (meaning <u>against</u> the temperature gradient).



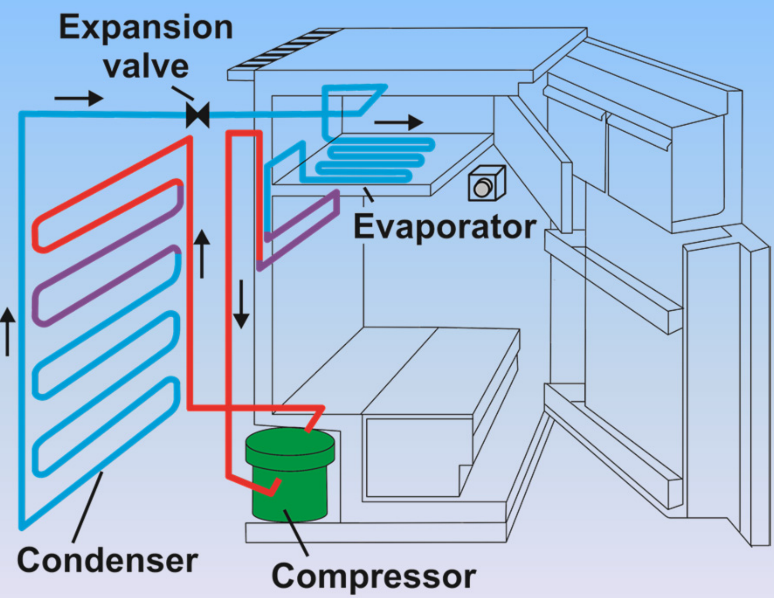
In order to avoid entropy generation all steps have to be *reversible*.

Refrigerator

Every refrigerator uses this principle to pump entropy from its interior into the warmer air outside, while the low-boiling coolant (operating as a kind of "entropy sponge") circulates in a closed circuit.



Principle of operation



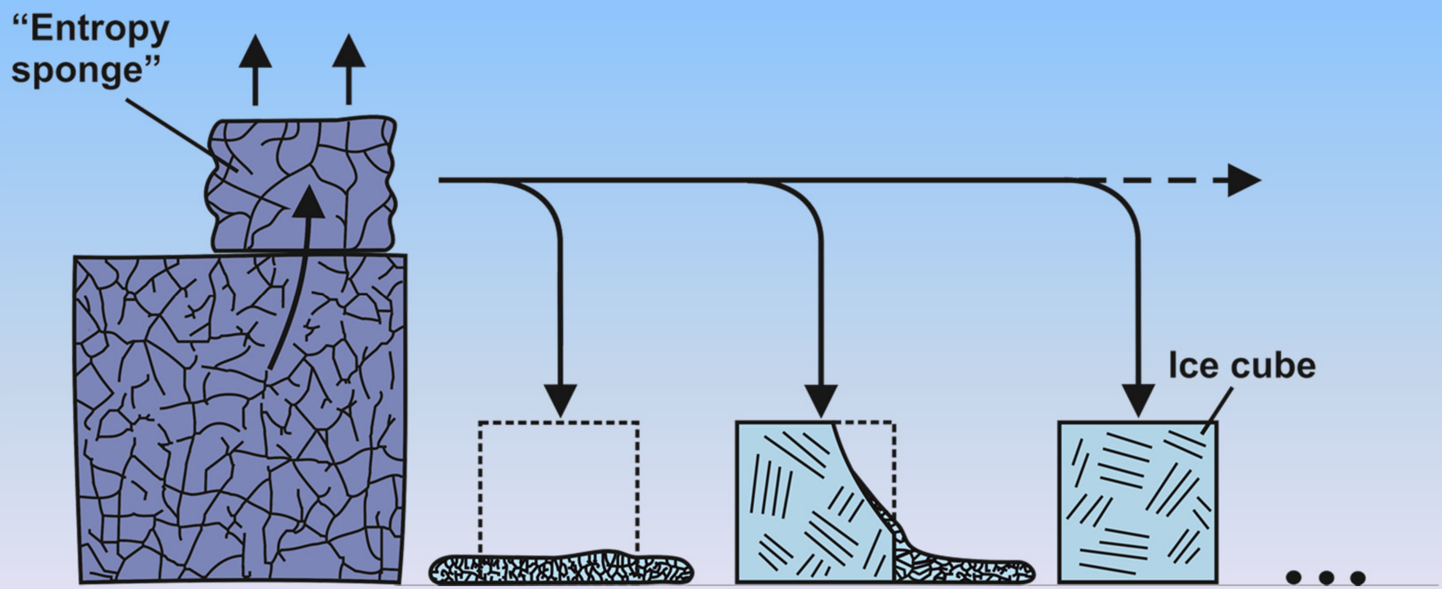
Technical realization

4. Measuring Entropy

Measuring Entropy

The transferability of entropy opens up a possibility of measuring the amount of it in an object.

For example, the amount of entropy needed to melt a given ice cube could serve as unit.

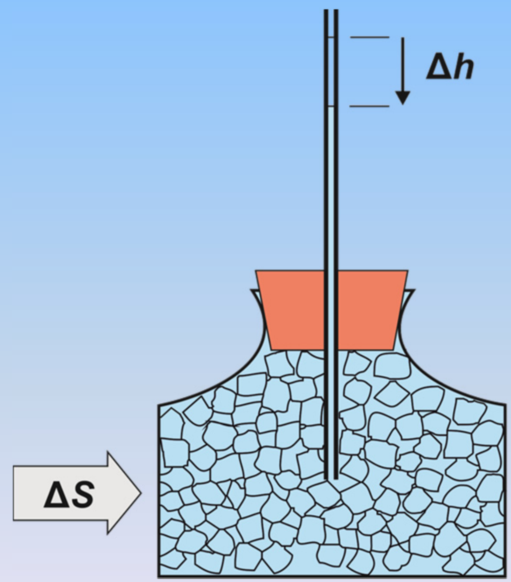


The amount of entropy which melts 0.893 cm^3 of ice corresponds exactly to the SI compatible unit 1 Ct (Carnot) (= 1 J/K).

Ice-Water Bottle

Instead of counting ice cubes, it is easier and more accurate to use the amount of melt water produced as measure.

A bottle with a capillary on it and filled with a mixture of ice and water can serve as a simple "entropy measurement device."

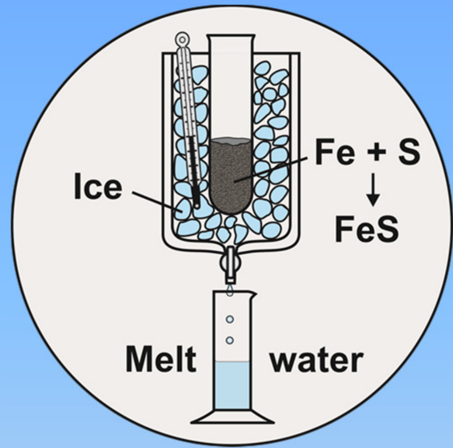


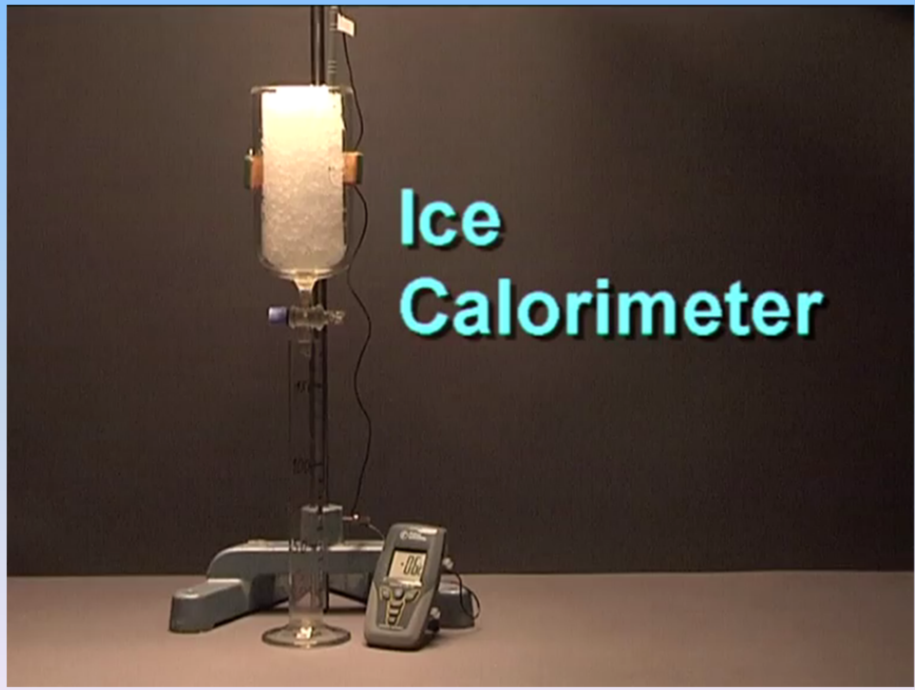
Because melt water has a smaller volume than ice the decrease in volume can be used to measure the supplied entropy.

Ice Calorimeter

Procedure:

The mixture of iron and sulfur powder in the test tube is ignited with a sparkler.





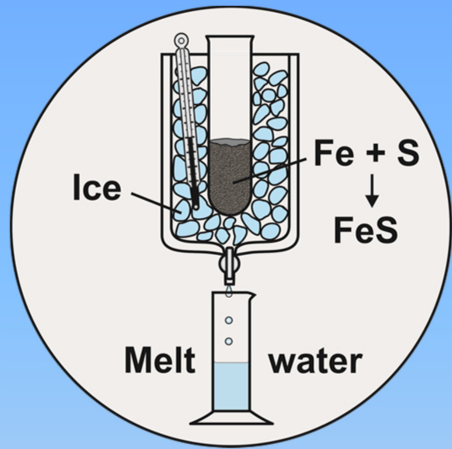
Ice Calorimeter

Procedure:

The mixture of iron and sulfur powder in the test tube is ignited with a sparkler.

Observation:

The mixture reacts thereby glowing red. Part of the ice melts. The temperature of the ice remains constant.



Explanation:

Iron reacts with sulfur to iron sulfide:

$$Fe|s + S|s \rightarrow FeS|s.$$

During the reaction a considerable amount of entropy is emitted. The volume of water collected in the graduated cylinder is indicative of this amount of entropy (0.82 mL of melt water corresponds to the unit of entropy).

5. Applying the Concept of Entropy

First Applications

Let us have a look at some examples that give an impression of the values of entropy.

A piece of blackboard chalk contains about 8 Ct (J/K) of entropy. If it is broken in half, each half will contain about 4 Ct because entropy is an extensive quantity.

A 1 cm^3 cube of iron also contains about 4 Ct, although it is considerably smaller;

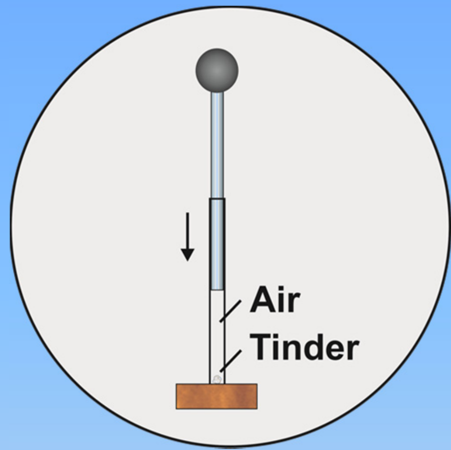
whereas, there is only about 8 Ct in 1 liter! of ambient air.

If the air is compressed to 1/10 of its original volume, it will become glowingly hot.

Fire Piston

Procedure:

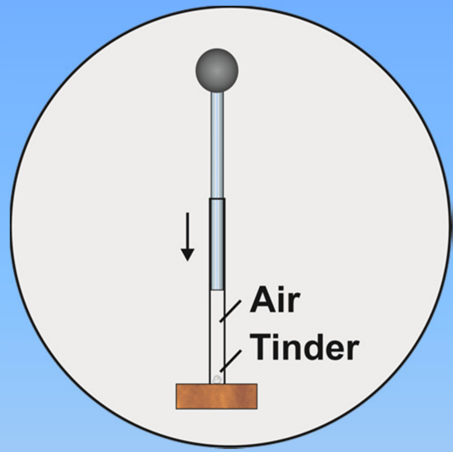
A small piece of tinder is poked into the hole in the lower piston. Subsequently, the upper piston is forced vigorously down.



Fire Piston

Procedure:

A small piece of tinder is poked into the hole in the lower piston. Subsequently, the upper piston is forced vigorously down.



Observation:

The tinder ignites with a bright flash.

Explanation:

When a fixed mass of gas such as air is compressed rapidly it becomes glowingly hot (*adiabatic compression*). (If this compression is not done quickly enough the entropy has time to flow from the hot gas into the cold cylinder walls and the gas cools down.) This effect can be used to ignite a piece of tinder. Thereby, the air in the cylinder acts simultaneously as an oxidizer.

Diesel Engine

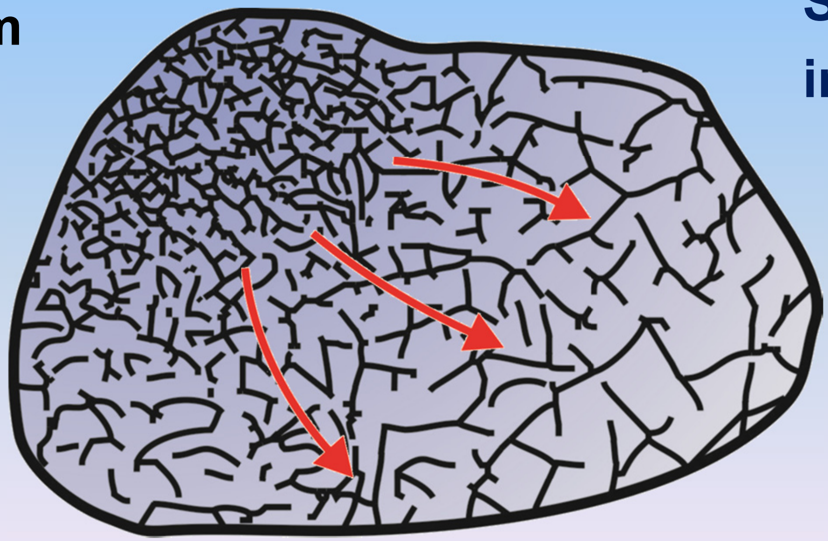
This effect can also be utilized in diesel engines to ignite the fuel-air mixture.

Entropy and Temperature

Temperature can be imagined as a kind of thermal "tension" weighing upon entropy and therefore as the cause of an entropy flow.

Example:

High thermal "tension"
Warm



Spreading of entropy in the body

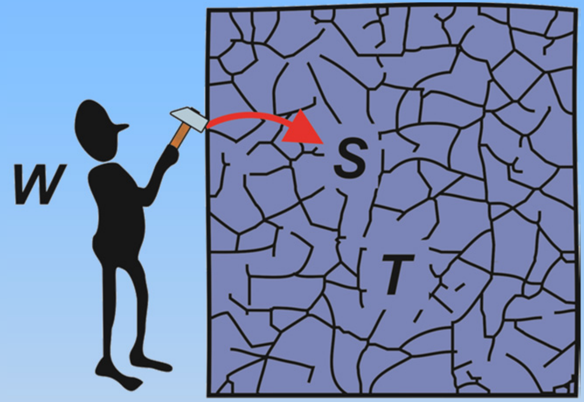
Low thermal "tension"
Cold

Entropy and Temperature

Energy is needed to force entropy into a body against this “tension” (e.g. by compressing an “entropy sponge”) (or to generate entropy in the body).

The higher the “tension” (the higher the temperature), the more energy is needed.

The amount of energy necessary also grows the more entropy is added or generated.



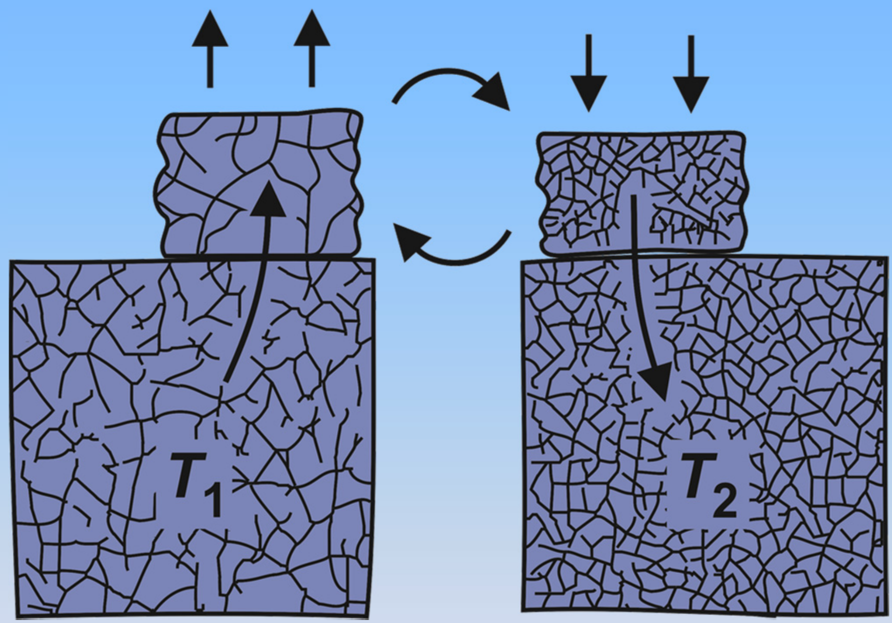
$$W = T \cdot S$$

Because energy and entropy are both measurable quantities, the “thermodynamic” temperature *T* has a well-defined value.

$$T = \frac{dW}{dS}$$

Energy for Entropy Transfer

The energy W_t needed to transfer an amount of entropy S_t from a body of lower temperature T_1 to a body of higher temperature T_2

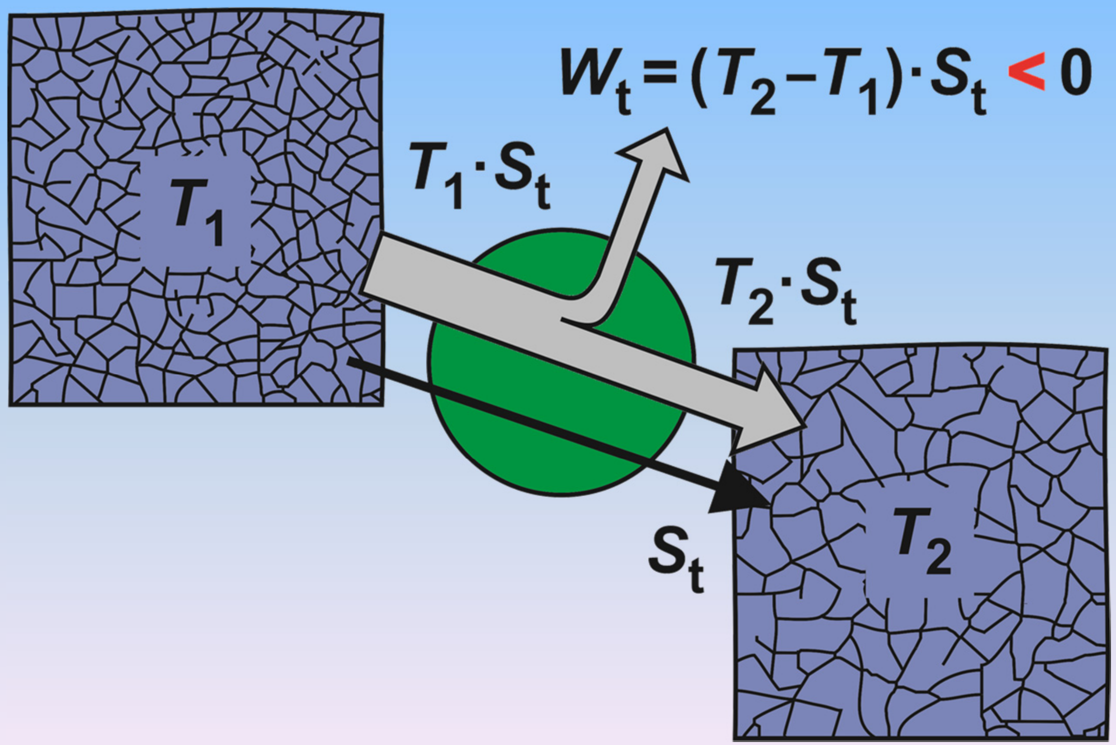


- **equals the energy $W_2 = T_2 \cdot S_t$ necessary to press the entropy into the warmer body**
- **minus the energy $W_1 = T_1 \cdot S_t$ gained when the entropy is removed from the colder body.**

$W_t = (T_2 – T_2) \cdot S_t > 0$ ***heat pump*** **(e.g. refrigerator)**

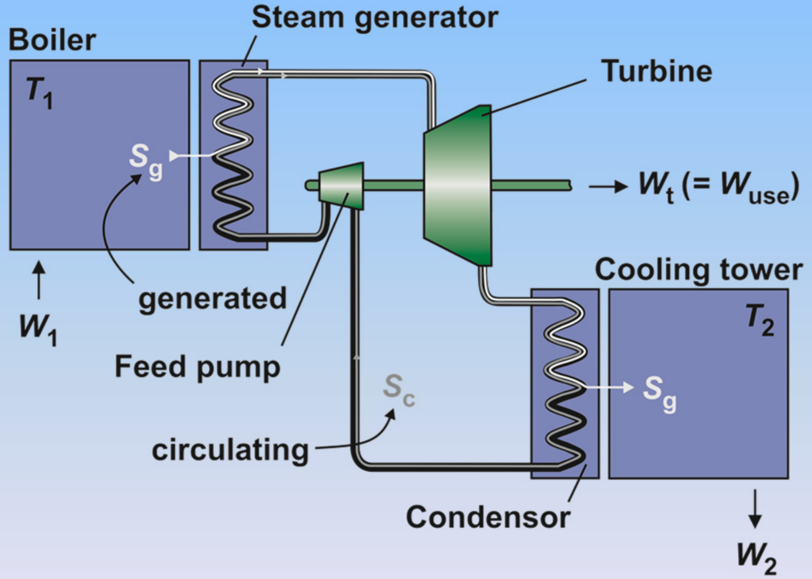
Heat Engines

A *heat engine,* in contrary, is a device that conveys entropy S_t from a body of higher temperature T_1 to a body with a lower temperature T_2. Thereby, the energy W_t is gained.

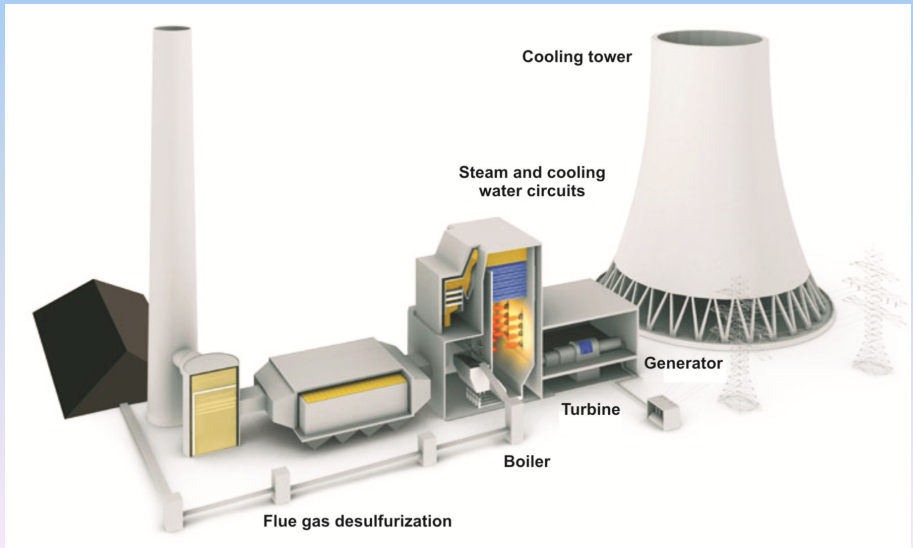


Thermal Power Plant

In a thermal power plant, for example, simplified the energy W_t (= W_{use}) is used which is gained during the transfer of entropy from the steam boiler to the cooling tower. The entropy itself is generated in the boiler by consumption of energy W_1 .



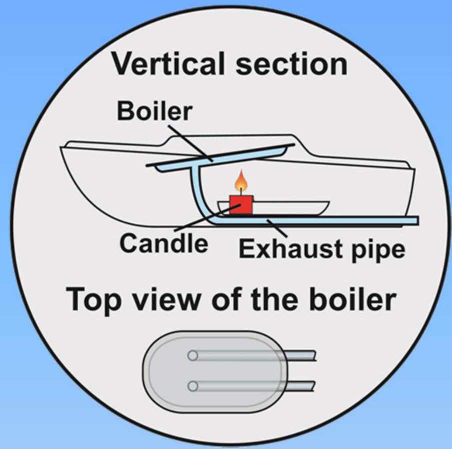
Simplified schematic diagram



Pop-Pop Steam Boat

Procedure:

The boiler of the boat is filled with water. Subsequently, the candle is lighted and the holder placed underneath the boiler.



Observation:

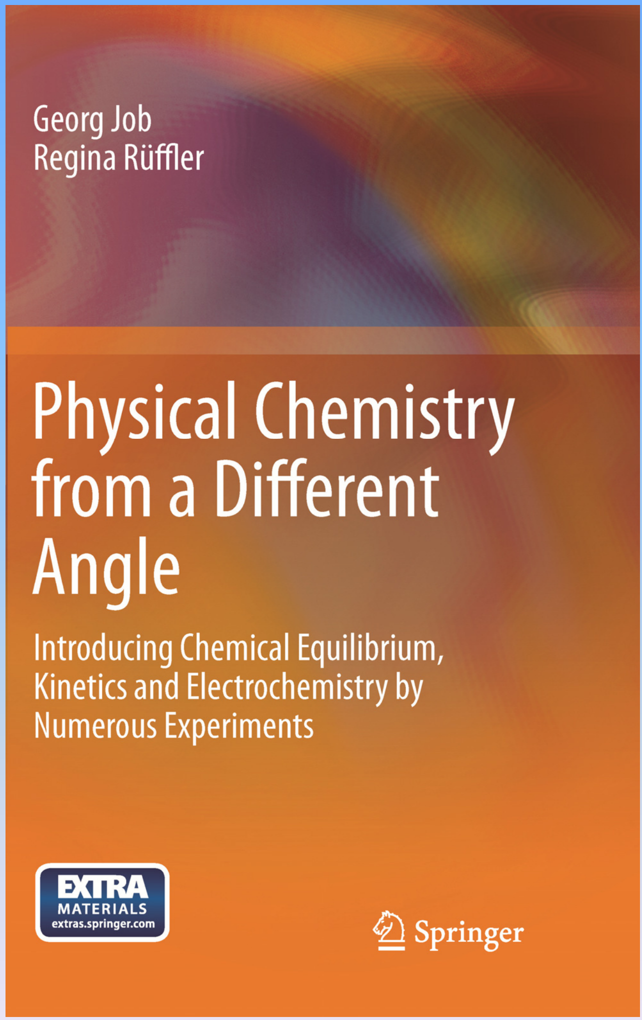
After a short while, the boat begins to move with the typical "popping" noise.

Explanation:

The pop-pop boat is powered by a very simple heat engine ("thermal motor") without moving parts. The released energy is used to operate the boat.

6. Outlook

6. Outlook



Georg Job, Regina Rüffler

Physical Chemistry from a Different Angle

An Introduction with New Concept and Numerous Experiments

published by Springer

641 pages, nearly 400 figures

ISBN 978-3319156651