Workshop

Teaching Entropy with Fun

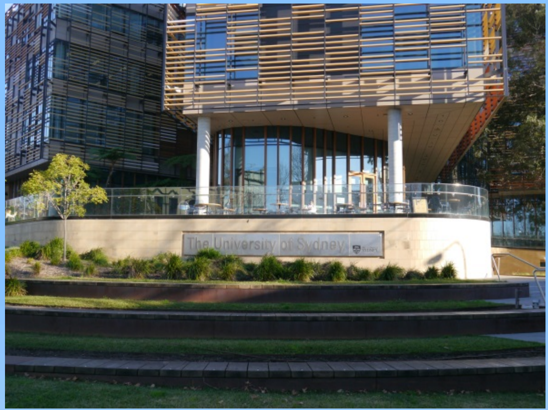
Regina Rüffler, Georg Job

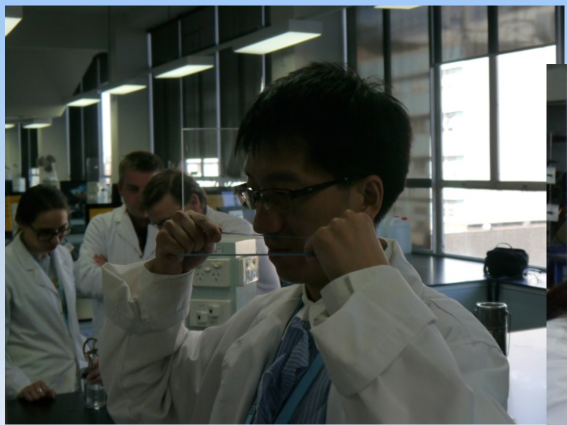
JOB FOUNDATION

c/o. Institute of Physical Chemistry,

University of Hamburg

Impressions from the Workshop
“ Teaching Entropy with Fun”





Outline

1. Introduction—Entropy
2. Macroscopic Properties of Entropy
3. Entropy Transfer
4. Measuring Entropy
5. Applying the Concept of Entropy
6. Entropy Conduction
7. 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.

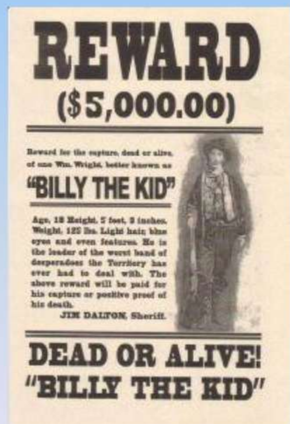
Therefore, it could be regarded as a kind of "black sheep" of the thermodynamic quantities.

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.

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

We propose to introduce *entropy S* as an in matter distributed, more or less mobile entity that 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 that has long been used for various basic quantities such as mass.

Application

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

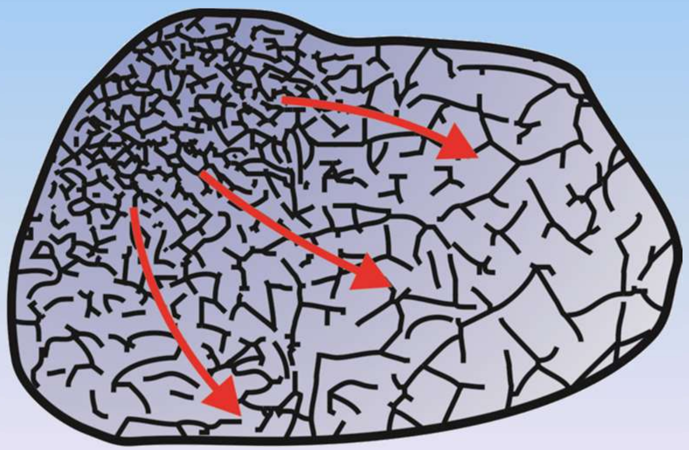
Numerous illustrative but nevertheless simple and safe demonstration experiments contribute essentially to deepen comprehension and forge links with everyday experiences.

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 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 feels 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.**

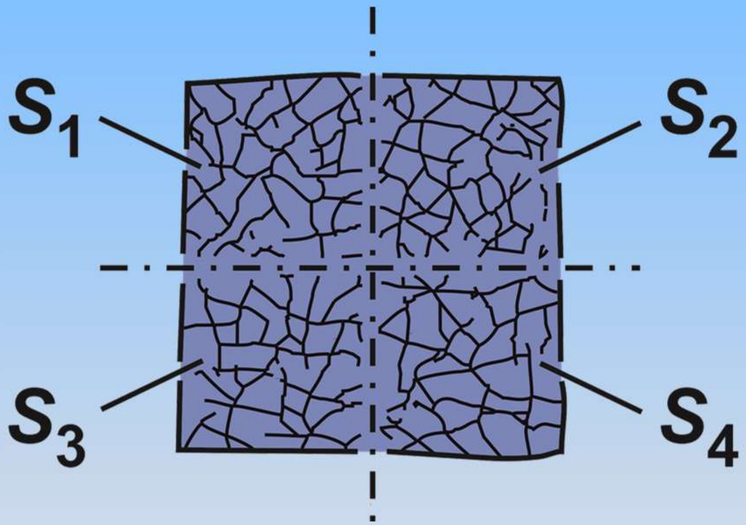
   Identical objects in the same state contain equal amounts of entropy.

$$S_1 = S_2 = S_3$$

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.



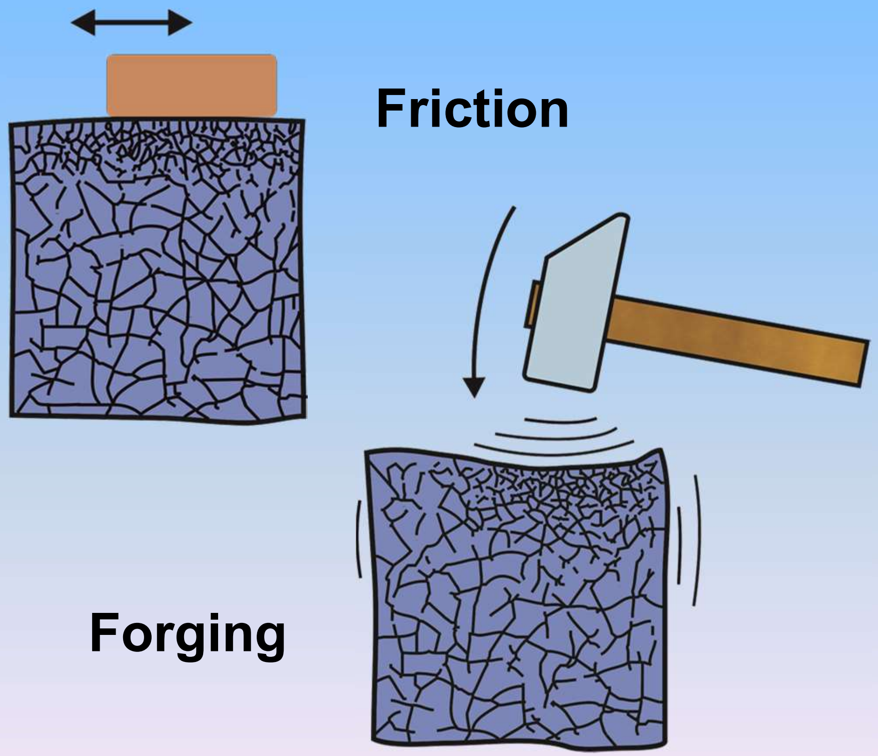
$$S_{total} = S_1 + S_2 + S_3 + S_4$$

in other words:

"Entropy is an *extensive quantity*."

"Wanted Poster" of Entropy

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



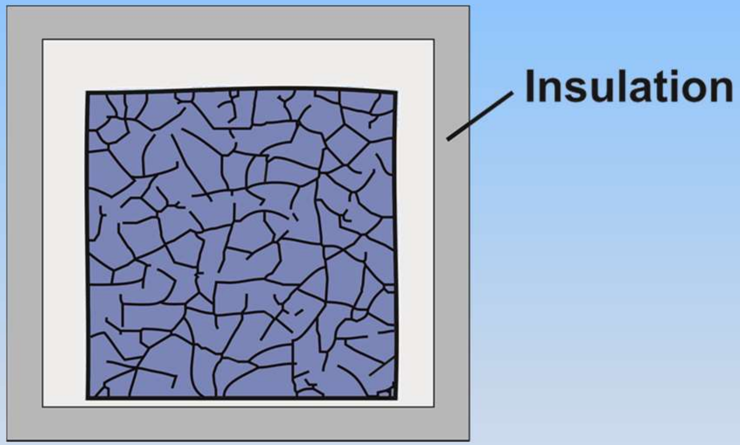
from: "Wanna bet, that..?"
(German Television Show)

(piece of iron became by strong hits with heavy hammers so hot that one could to prepare a fried egg on it)

"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.



$$\Delta S \geq 0$$

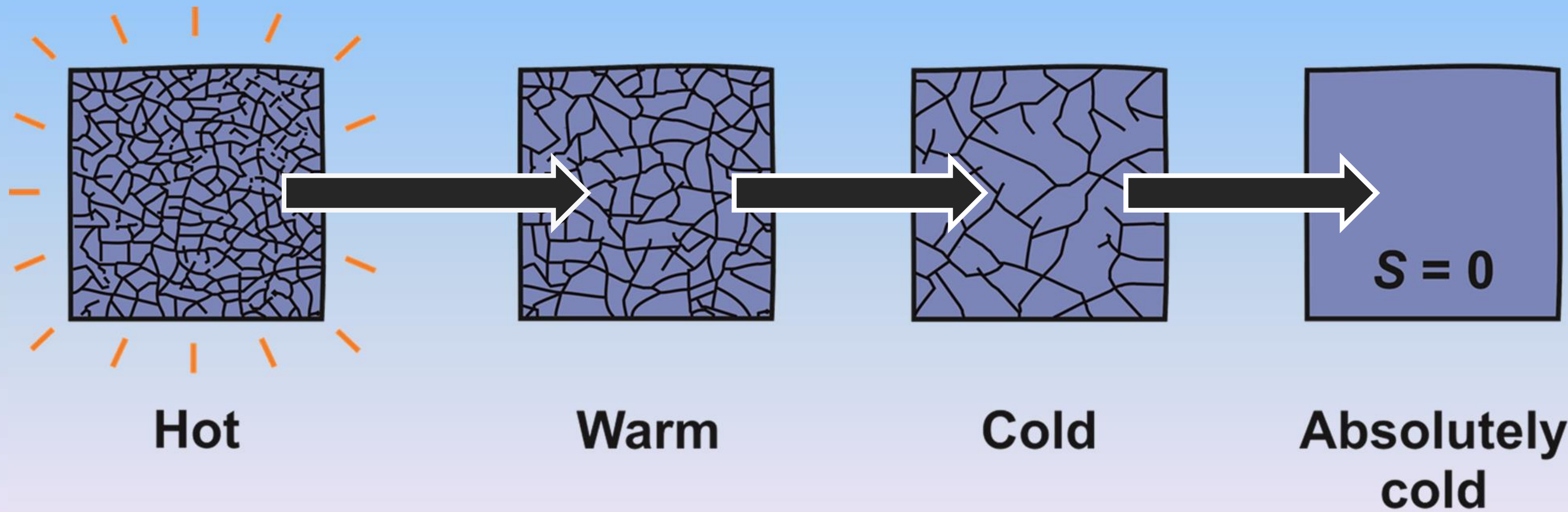
also known as

"***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.



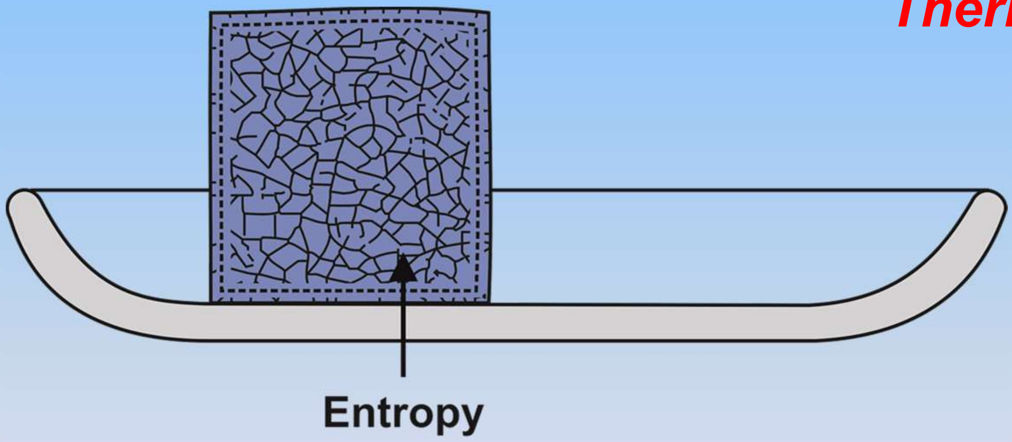
Entropy flows spontaneously from a warmer to a colder object.

"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*.

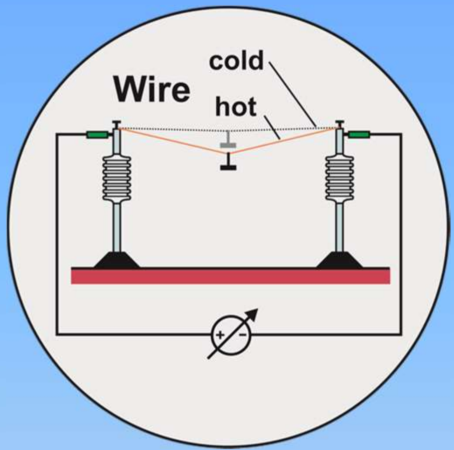
Thermal expansion

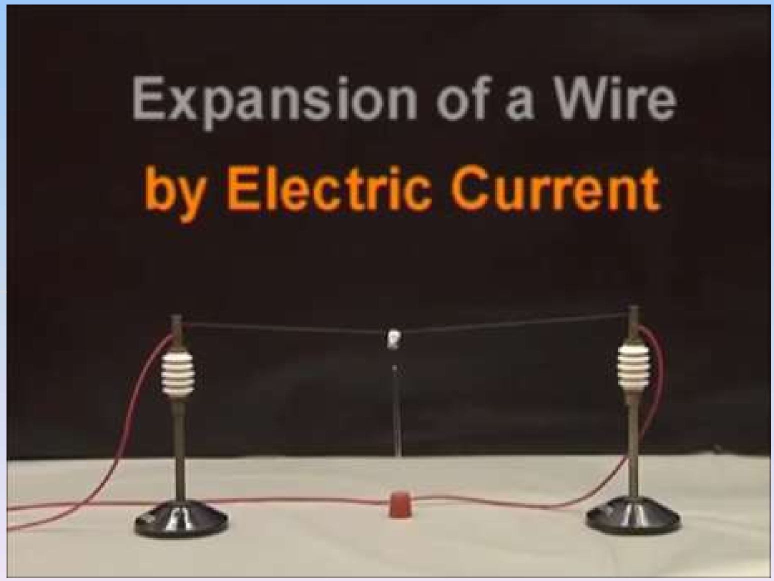


Expansion of a Wire by Electric Current

Procedure:

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





https://www.job-stiftung.de/index.php?experiment-3.3-expansion-of-a-wire-caused-by-electric-current

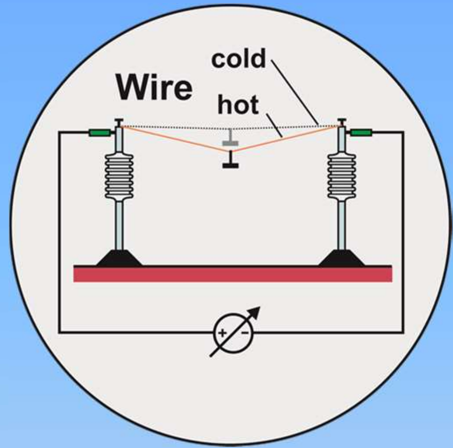
Expansion of a Wire by Electric Current

Procedure:

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

Observation:

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



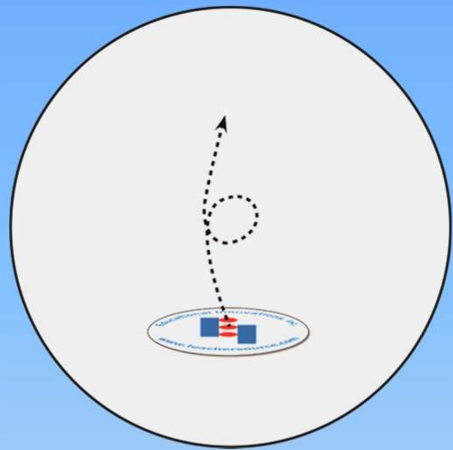
Explanation:

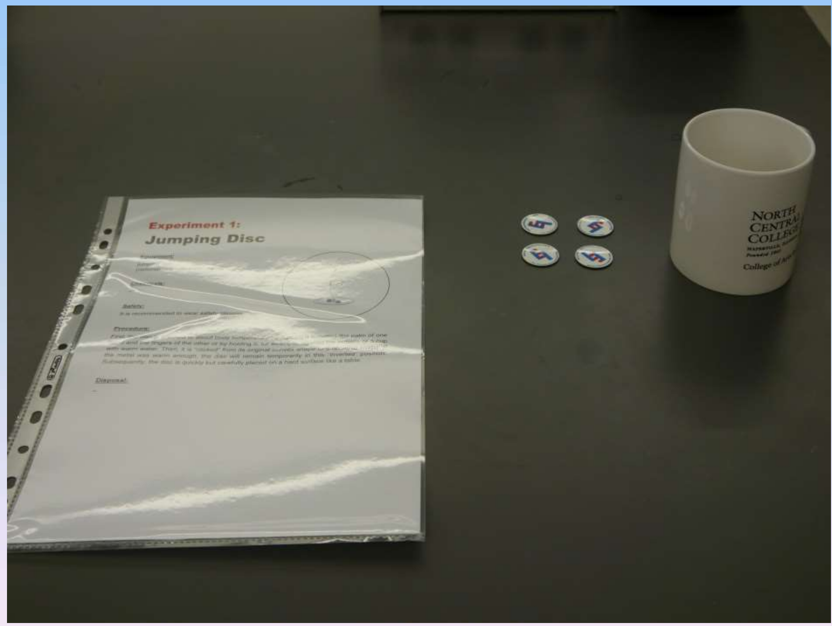
Entropy is generated by the electric current. As *main effect* of the increase in entropy the wire becomes warmer and finally begins to glow. But the increasing entropy also causes a *side effect*: The wire lengthens noticeably. If the electric current is decreased again, also the entropy generated in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

Jumping Disc

Procedure:

The disc is warmed and subsequently "clicked" into the "inverted" shape. Then, the disc is placed on the table.



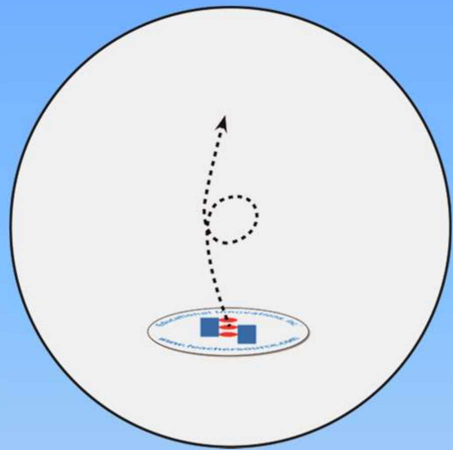


Jumping Disc

1

Procedure:

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

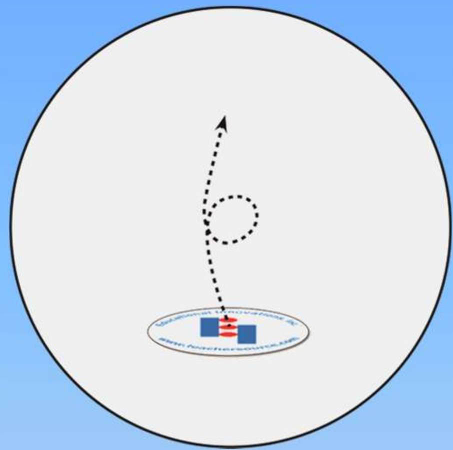


https://www.youtube.com/watch?v=ECReCtxOqJY

Jumping Disc

Procedure:

The disc is warmed and subsequently "clicked" into the "inverted" shape. Then, 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 about 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.

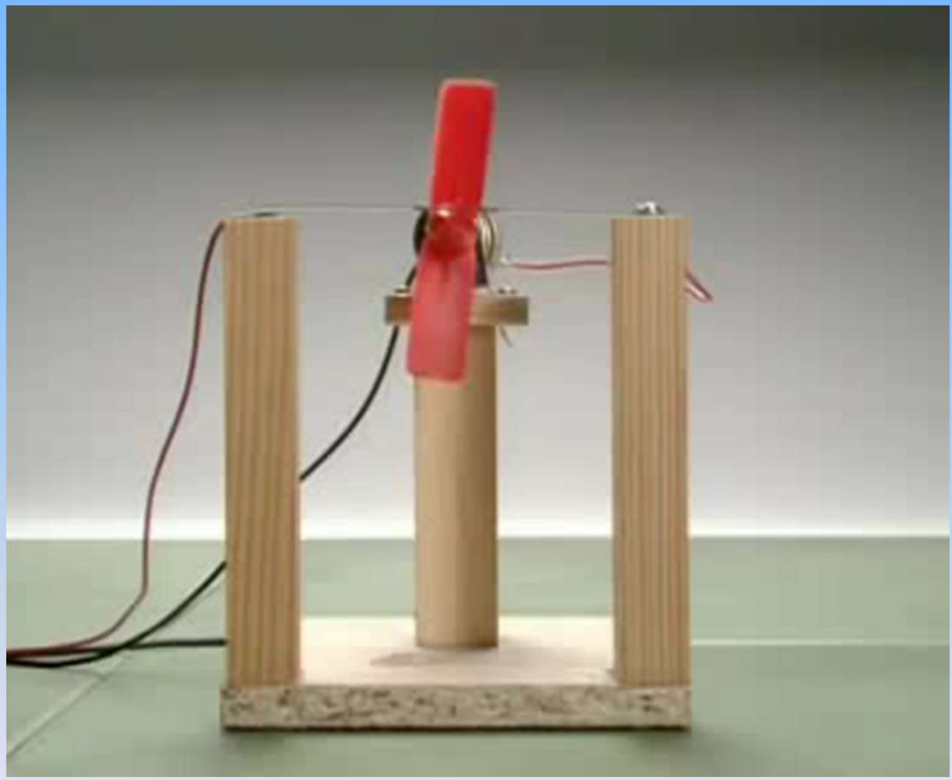
Bimetallic Strip

Expansion due to the addition of entropy

https://www.youtube.com/watch?v=82FPQ6z8vcE

Thermostat

Bimetallic strips are used, for example, in thermostats.

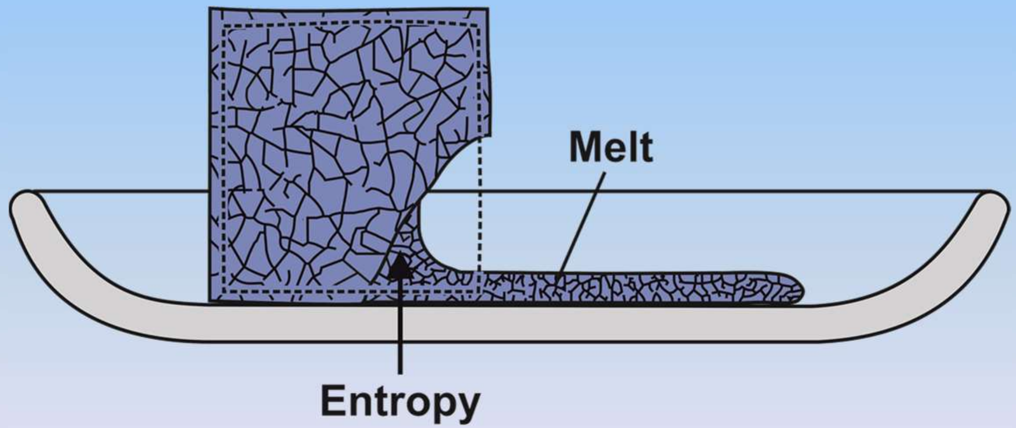


https://www.youtube.com/watch?v=EkQ2886Sxpg (part from 1:52 on)

“Wanted Poster” of Entropy

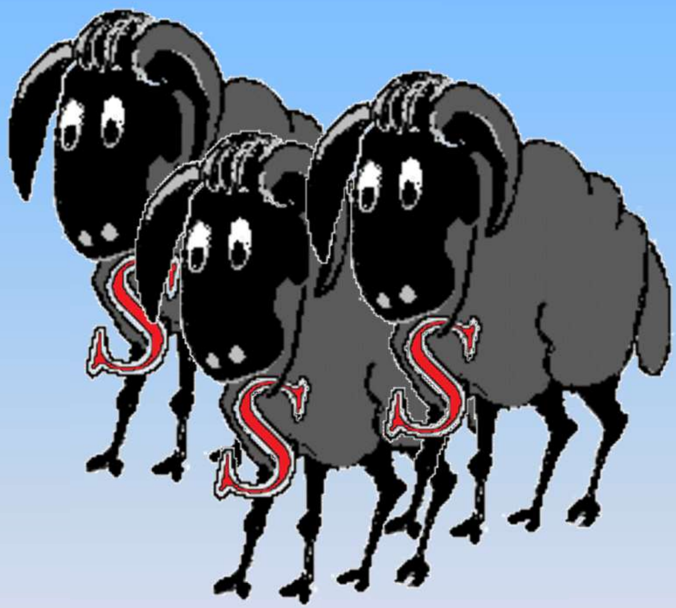
7. **If the entropy is continously increased, the substance will finally *melt* (*change in state of aggregation*).**

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



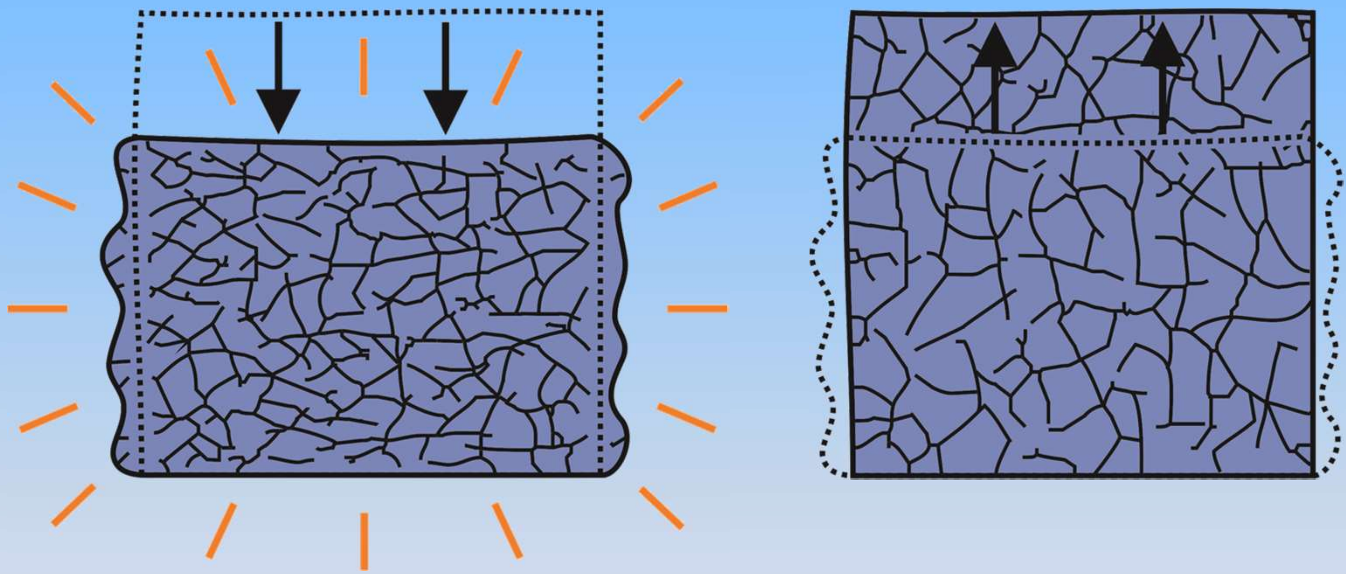
If a substance changes completely from solid to liquid state at its melting point, the entropy inside it increases by a *given* amount.

3. Entropy Transfer



Entropy and Volume

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

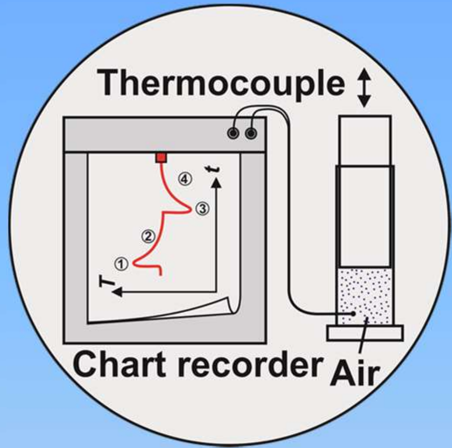


These compression and expansion effects can be especially well observed in substances that can be easily compressed such as gases.

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.

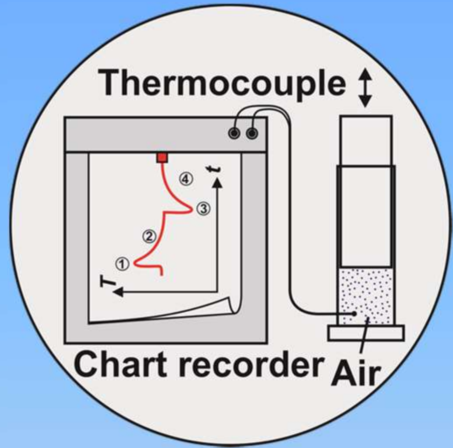


https://www.job-stiftung.de/index.php?experiment-3.4-compression-and-expansion-of-air

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).

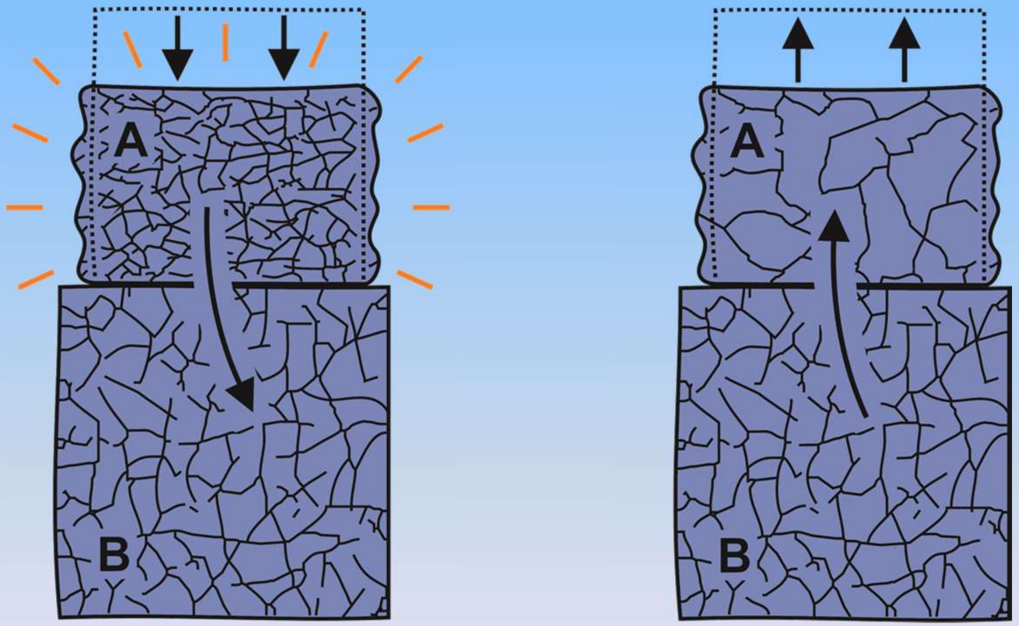
The expansion of the piston leads to a further cooling (phase 3).

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 …

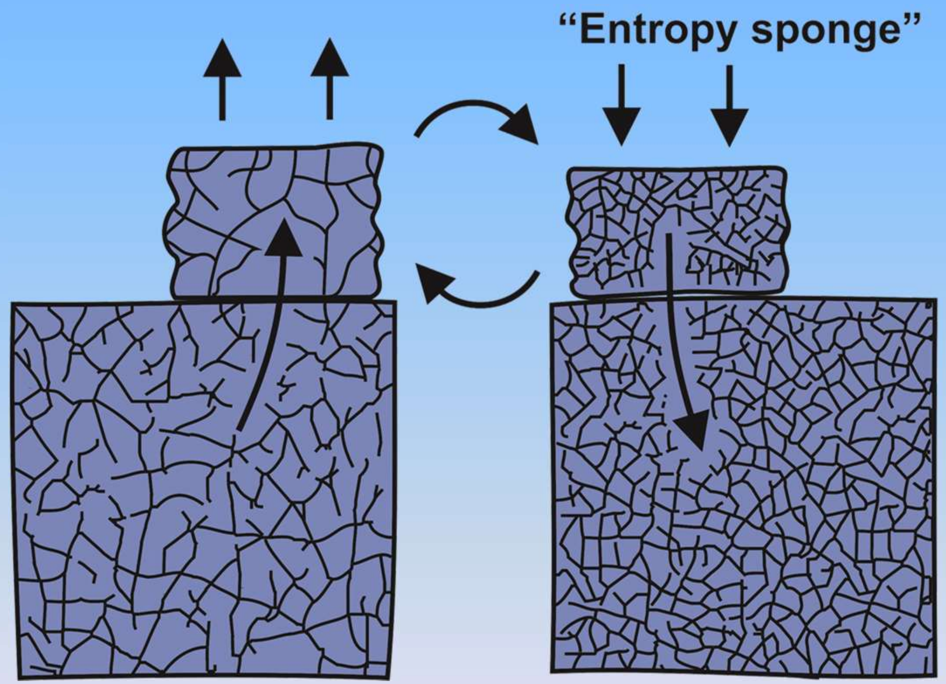
and takes entropy up on expansion.



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

Entropy Transfer

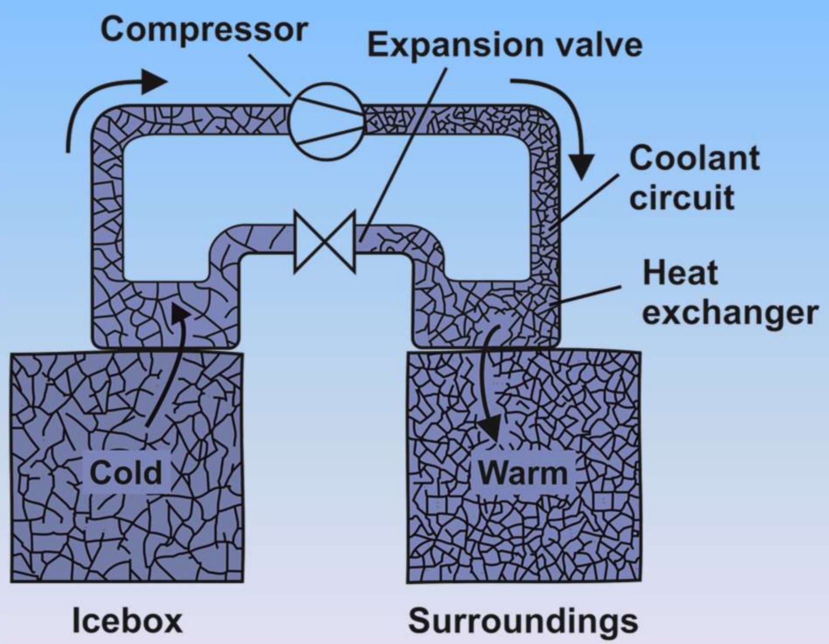
Such an "entropy sponge" can be used to transfer entropy from a cold to a hot object (meaning <u>against</u> the temperature gradient).



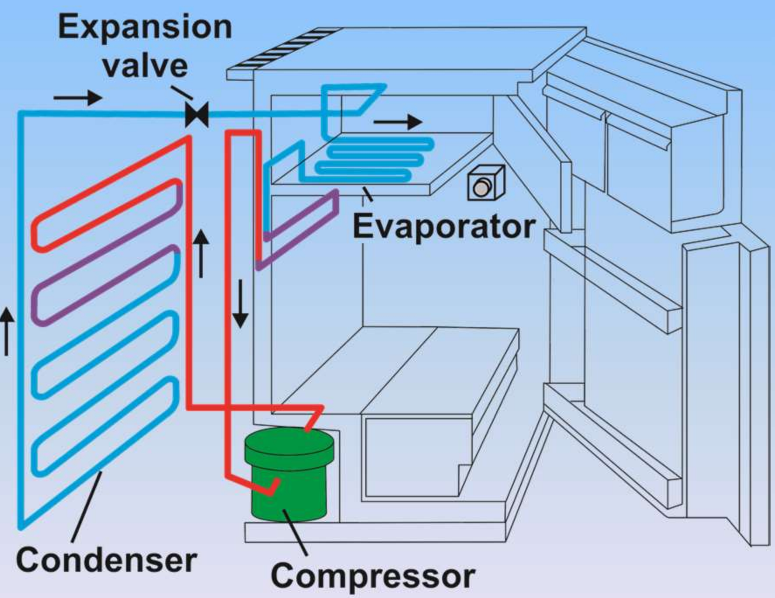
In order to avoid entropy generation all steps have to be *reversible*.

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

How a Refrigerator Works

https://www.youtube.com/watch?v=se1XZ8D_fCM

Increase of Entropy

In summary, we have found that the entropy content S of an object can basically increase in two ways:

- **through the entropy S_g *generated* inside (*irreversible* process)**
- **by the entropy S_e *exchanged* with the surroundings (*reversible* process)**

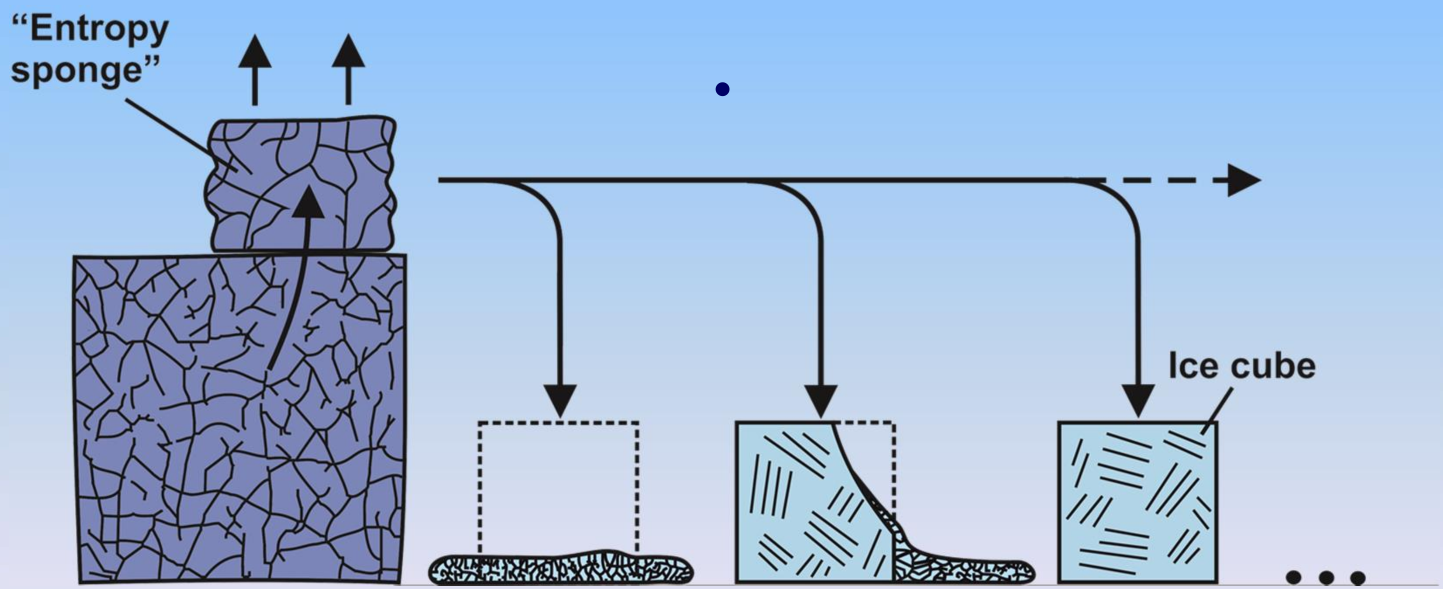
$$\boxed{\Delta S = S_g + S_e}$$

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.

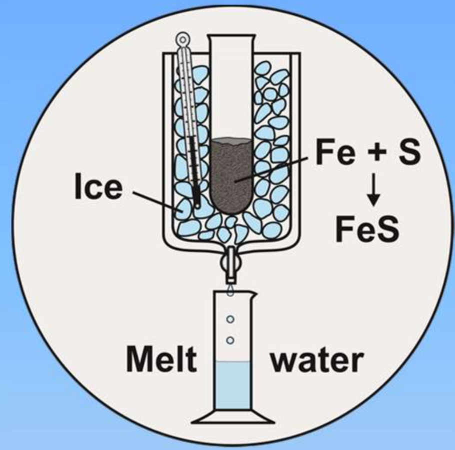


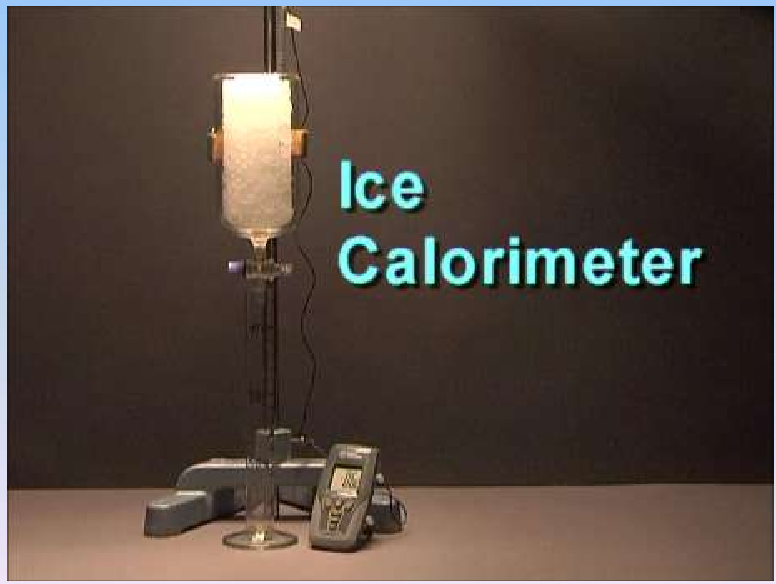
The amount of entropy that melts 0.893 cm^3 of ice corresponds exactly to the SI compatible unit 1 Ct (Carnot) (= 1 $J\,K^{-1}$).

Ice Calorimeter

Procedure:

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





https://www.job-stiftung.de/index.php?experiment-3.5-ice-calorimeter

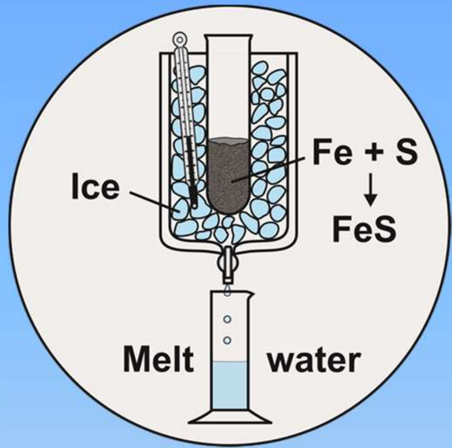
Ice Calorimeter

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:

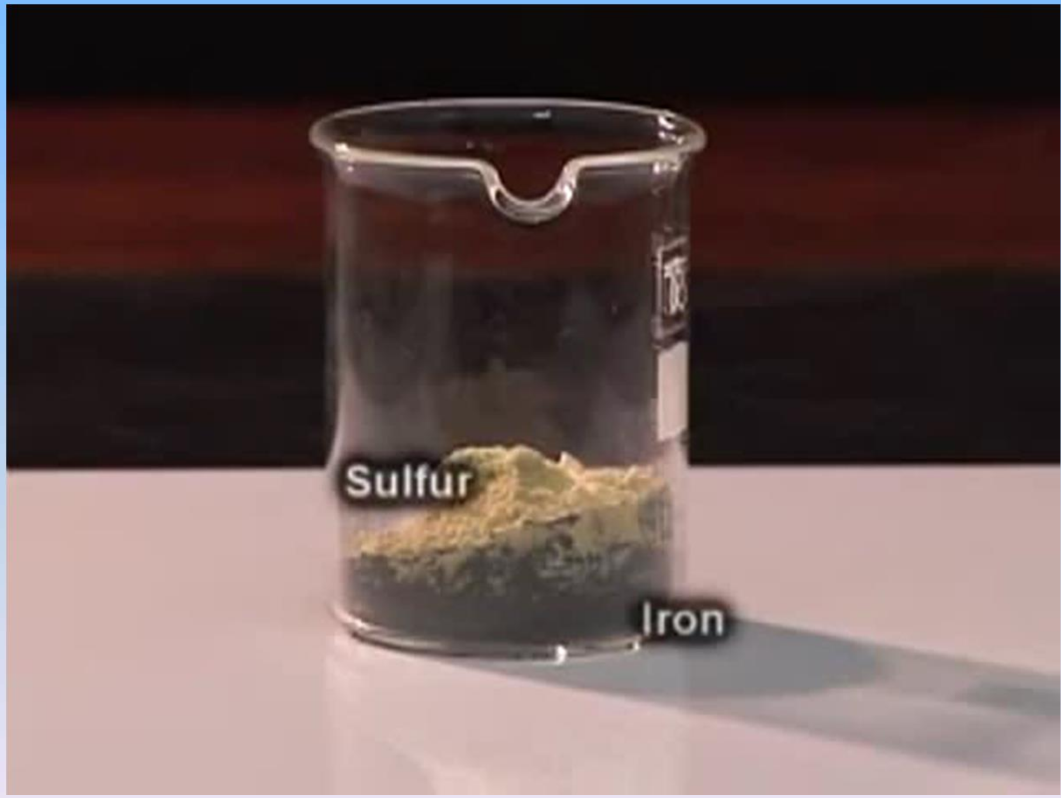
$$Fe|s + S|s \rightarrow FeS|s.$$

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).

Short “Intermezzo”

Reaction of iron and sulfur to iron sulfide:

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



https://www.youtube.com/watch?v=A5H6DVe5FAI

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 ($J\,K^{-1}$) 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.

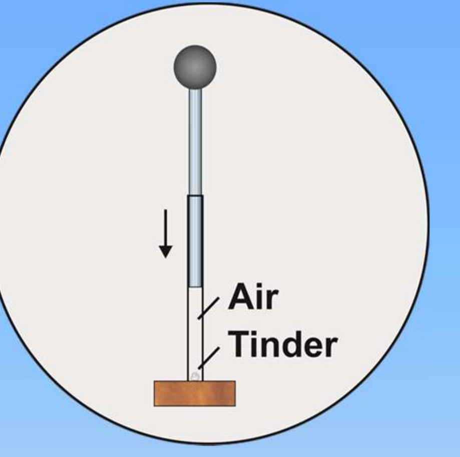
If the air is compressed to 1/10 of its original volume, it will become glowingly hot.

Fire Piston

2

Procedure:

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

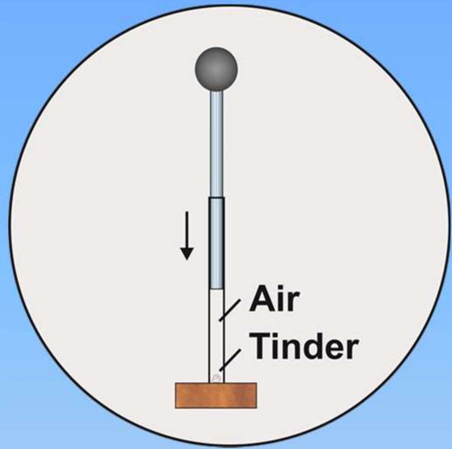


Fire Piston

2

Procedure:

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

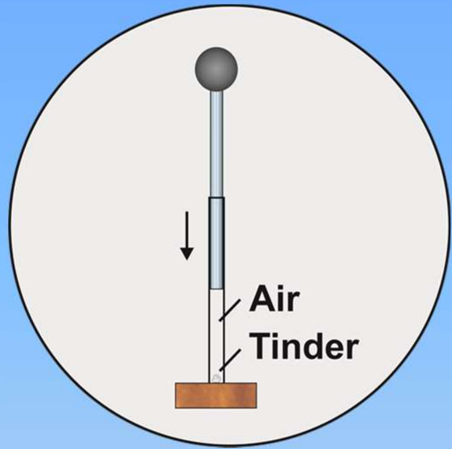


https://www.job-stiftung.de/index.php?experiment-3.7-fire-piston

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 a 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.

http://www.oldtimer-tv.com/oldtimer/DE/oldtimer/index.php?Seite=31

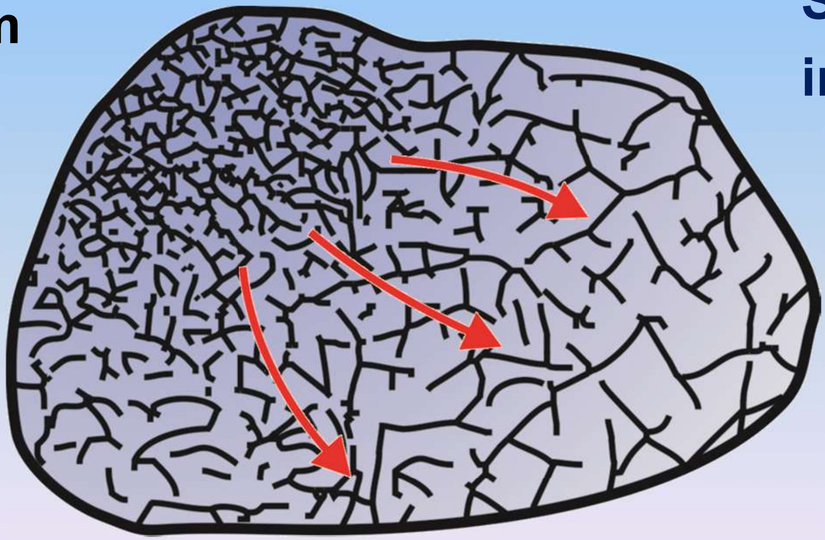
Entropy and Temperature

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 an object

Low thermal "tension"

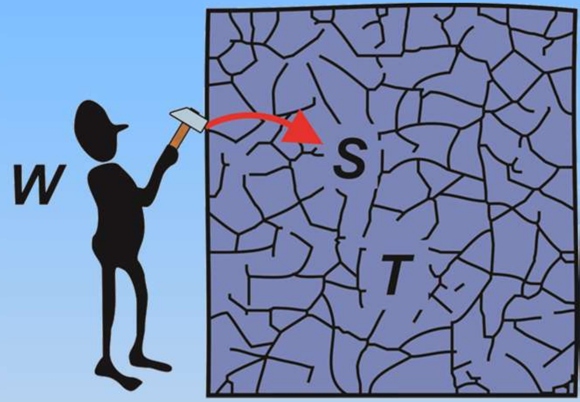
Cold

Entropy and Temperature

Energy is needed to force entropy into an object against this "tension" (e.g. by compressing an "entropy sponge") (or to generate entropy in the object).

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.



$$W = T \times S$$

Since energy and entropy are both measurable quantities, the "thermodynamic" temperature T has a well-defined value.

$$T = \frac{\mathrm{d}W}{\mathrm{d}S}$$

Energy for Generation or Exchange of Entropy

In more detail, we can write:

$$W = T \times S_g \qquad \text{or} \qquad W = T \times S_e$$

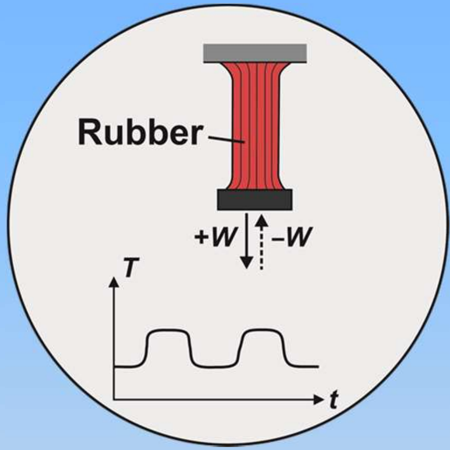
Despite their similarity, these two equations describe two rather different processes.

Since entropy can increase but cannot be destroyed a process that generates entropy (S_g) can only run in one direction, it is *irreversible*. The energy W used cannot be retrieved (except indirectly).

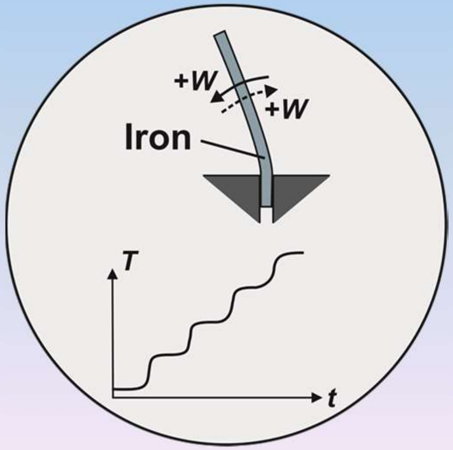
However, when entropy S_e from one object is transported into another at constant temperature T, the energy W is transferred with it. The energy, which was transferred, returns to the original object again along with the entropy flowing back to it. This process is *reversible*.

Conserving and Generating Entropy

To improve understanding, we will contrast an entropy conserving process with one that generates entropy.



If a rubber band is repeatedly expanded and then relaxed, its temperature changes periodically. The energy expended at the beginning is retrievable. The temperature change *T*(*t*) resembles a square wave. This process is *reversible*.



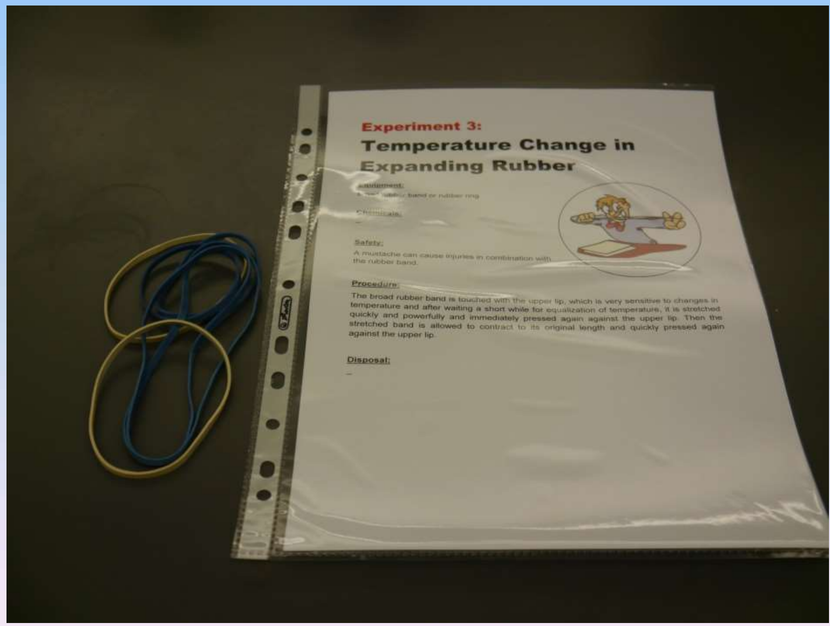
Bending an iron rod back (after previous bending) costs again energy and therefore, the temperature rises in steps. This process is *irreversible.* Although the rod returns to its original position, it is now warmer. Entropy is being generated and the energy involved is used up.

Temperature Change in Expanding Rubber

3

Procedure:

A rubber band is touched with the upper lip, stretched quickly and pressed again against the upper lip. Then, the stretched band is allowed to contract and pressed once more against the upper lip.



Temperature Change in Expanding Rubber

Procedure:

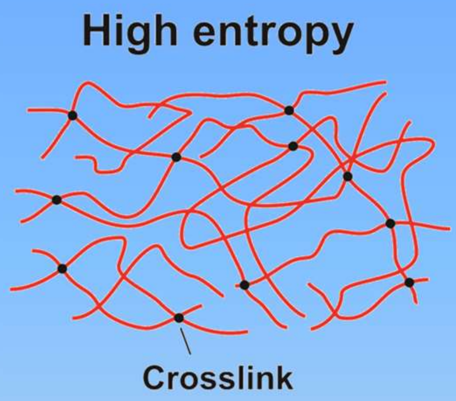
A rubber band is touched with the upper lip, stretched quickly and pressed again against the upper lip. Then, the stretched band is allowed to contract and pressed once more against the upper lip.

Observation:

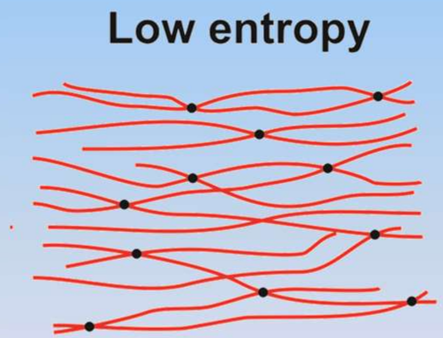
When the rubber band is stretched it feels noticeably warm. However, when the stretched band is allowed to contract there is a noticeable cooling.

Rubber and Entropy

Rubber consists of very long chains of polymerized molecules. The chains are held together by weak intermolecular forces but also by covalent disulfide bonds (crosslinks). The crosslinks prevents the polymer chains from moving independently. In the unstressed state, the chains are wildly tangled up.



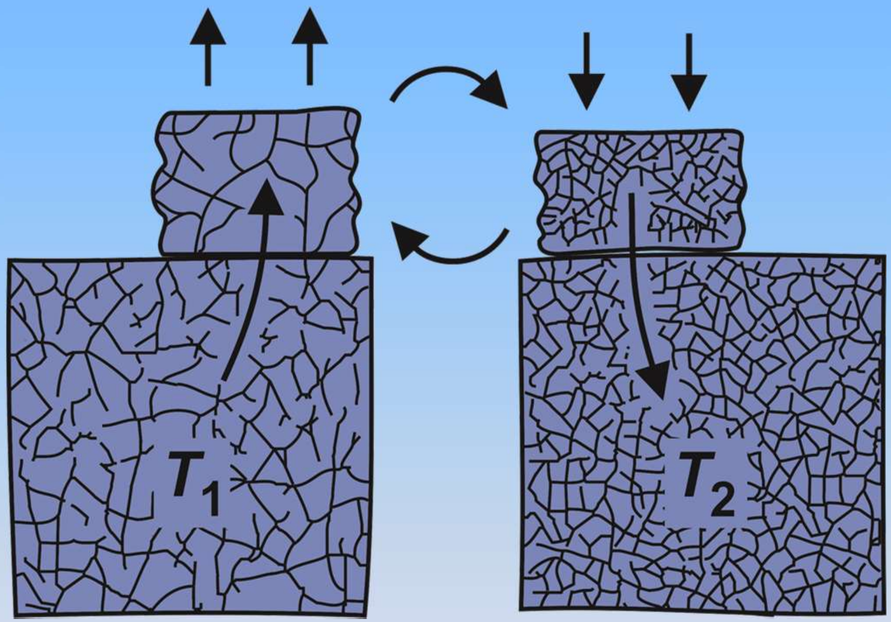
If one stretches the rubber, the messy tangles line up to a certain degree; the disorder and therefore the entropy decreases. The excess entropy is transferred to the environment what causes the observed increase in temperature.



When the rubber band relaxes, the polymer chains curl up again; the required entropy is "soaked up" from the environment what is the cause for the decrease in temperature.

Energy for Entropy Transfer

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



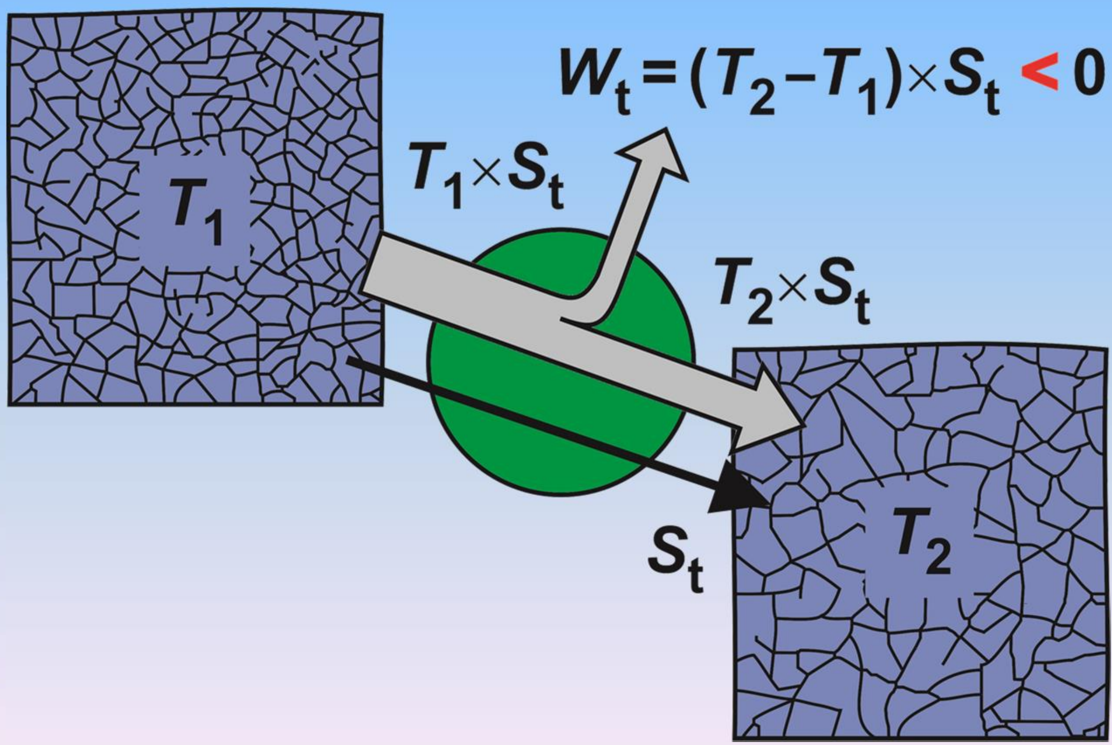
- **equals the energy $W_2 = T_2 \times S_t$ necessary to press the entropy into the warmer object**
- **minus the energy $W_1 = T_1 \times S_t$ gained when the entropy is removed from the colder one.**

$$W_t = (T_2 - T_1) \times S_t > 0$$

heat pump **(e.g. refrigerator)**

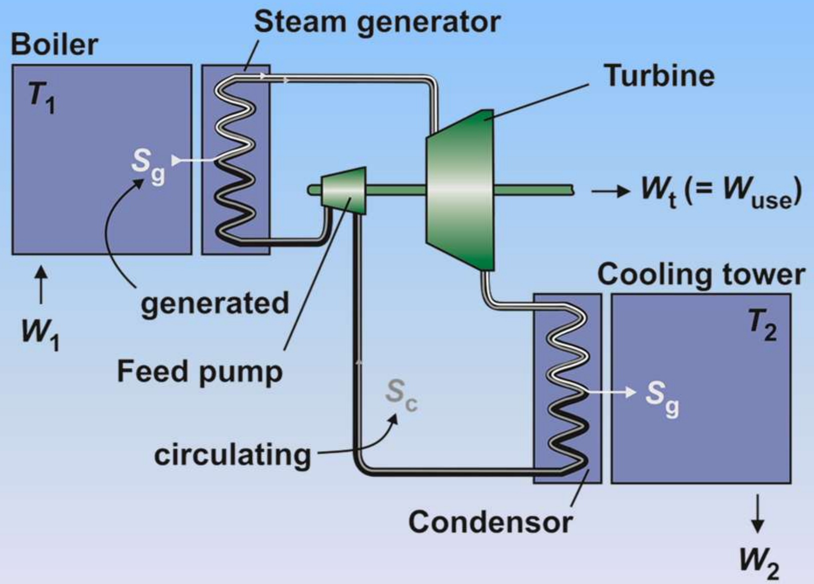
Heat Engines

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

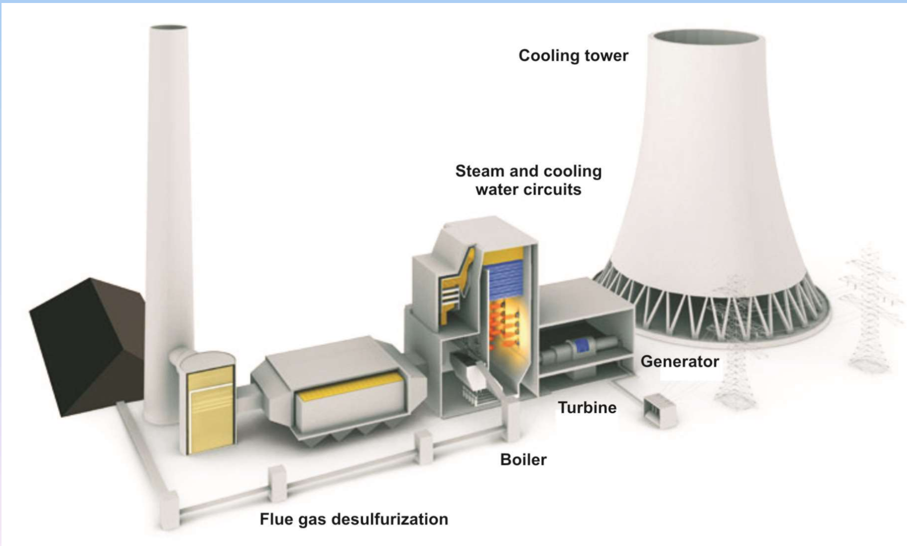


Thermal Power Plant

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 .



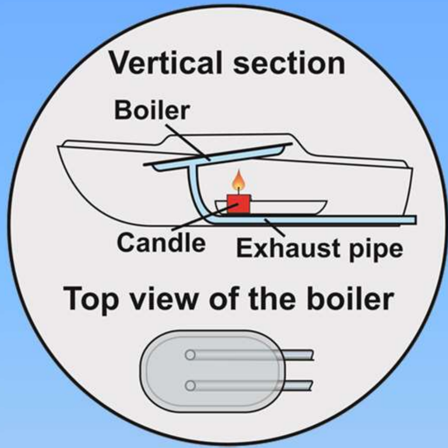
Simplified schematic diagram

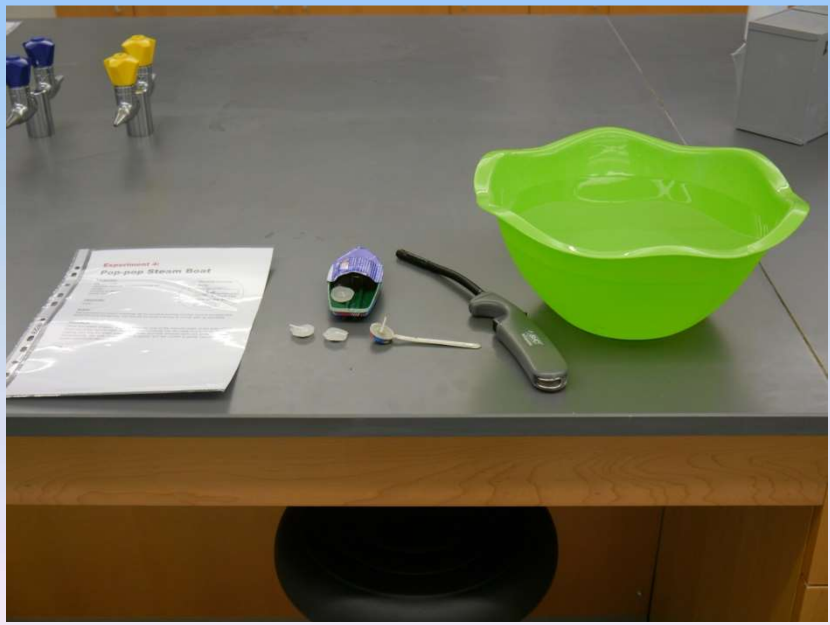


Putt-Putt Steam Boat

Procedure:

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

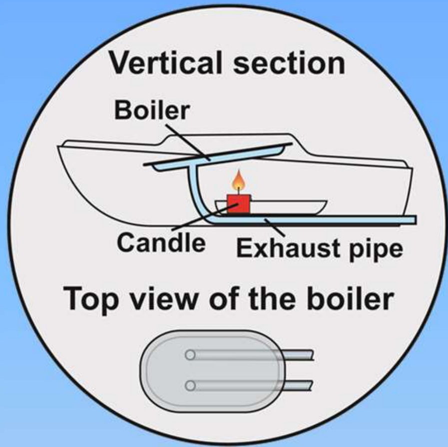




Putt-Putt Steam Boat

Procedure:

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



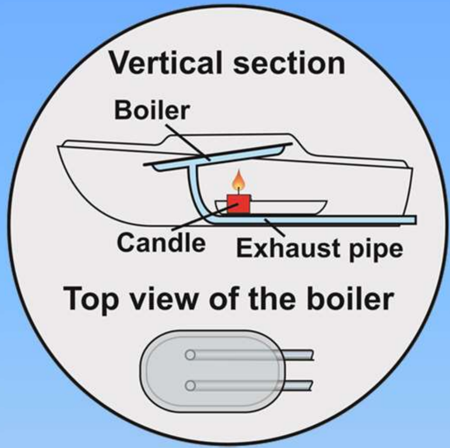
4

https://www.facebook.com/1585599751517333/videos/339908616926248

Putt-Putt Steam Boat

Procedure:

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



Observation:

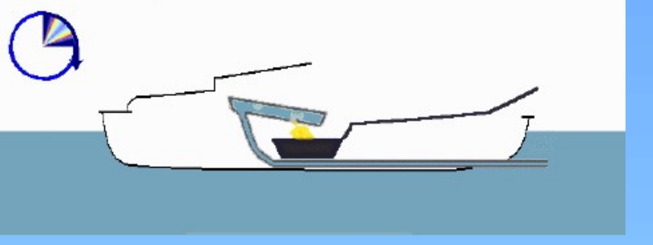
After a short while, the boat begins to move with the characteristic "putt-putt" sound.

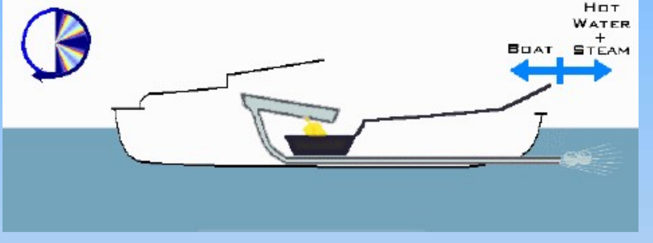
Explanation:

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

Putt-Putt Steam Boat

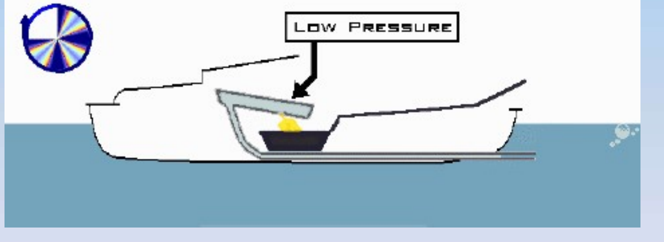
In the beginning of the cycle the water in the boiler is heated by the candle.

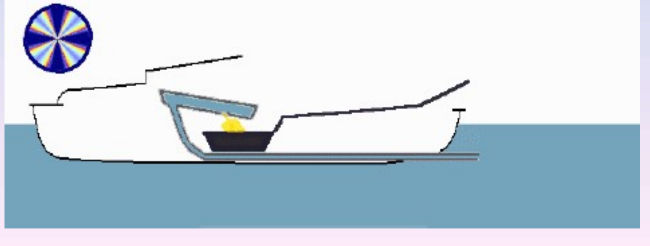




When the water boils it creates a brief burst of wet steam, which is expelled through the pipes in the rear of the boat and the boat moves forward.

Upon leaving the boiler, some of the steam condenses in the cooler part of the pipes thereby creating a partial vacuum .

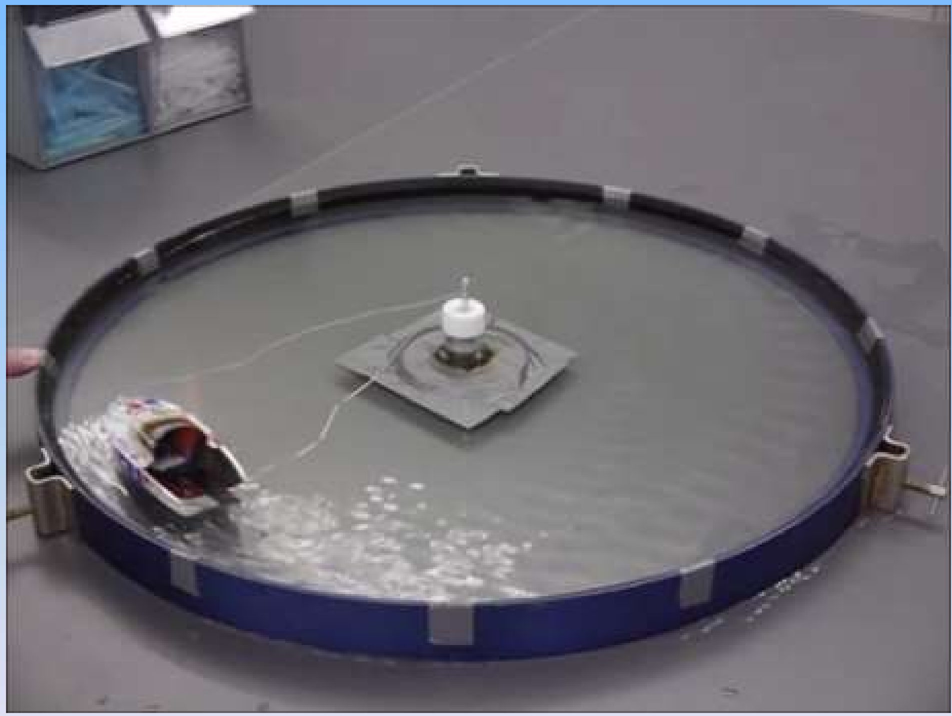




This results in a refilling of the pipes and the boiler with water. The cycle can begin again.

Putt-Putt Steam Boat Race

The putt-putt steam boat can also be used to test the efficiency of different combustible liquids like ethanol, butanol, biodiesel etc.



https://www.facebook.com/1585599751517333/videos/3490434704429104

Ponyo´s Boat

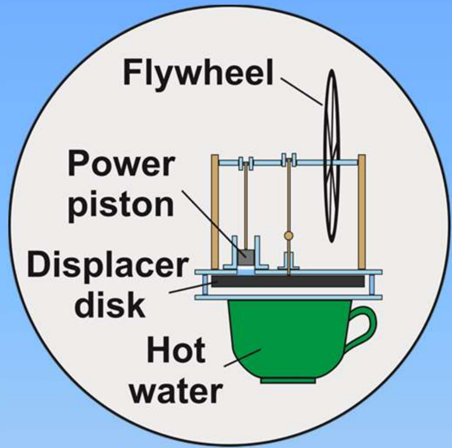
But there is also a surprising sighting of the boat in the world of cinema. The Japanese animator Hiyao Miyazaki has used it in his film “Ponyo.” Sōsuke a little boy owns a putt-putt boat that he is fond of, and during a crisis, it grows by the power of magic large enough for two children to ride in.

Low Temperature Stirling Engine

5

Procedure:

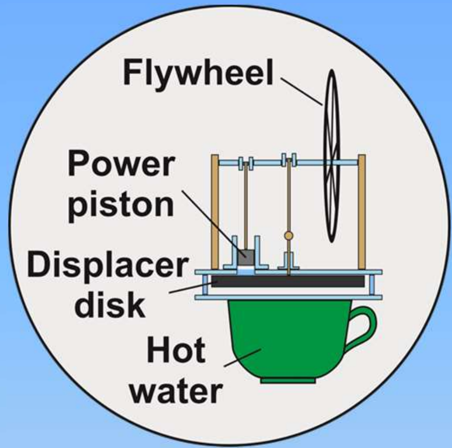
The Stirling engine is placed on top of a cup with hot water. After waiting for a short while, the flywheel is gently pushed.



Low Temperature Stirling Engine

Procedure:

The Stirling engine is placed on top of a cup with hot water. After waiting for a short while, the flywheel is gently pushed.



Observation:

The Stirling engine runs as long as the water in the cup is warm enough.

Explanation:

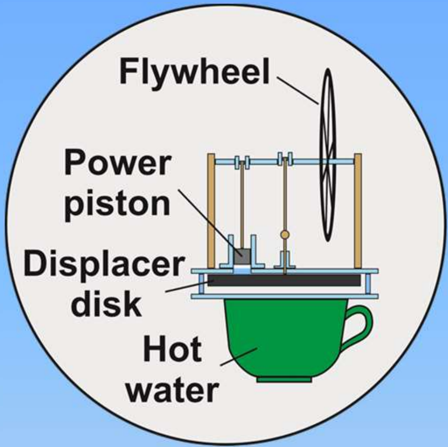
Stirling engines operate with a temperature difference between the plates. The displacement of the air from the hot to the cold region of the engine and vice versa by means of the displacer disk causes a periodic compression and expansion of the gas, which in turn results in a periodic movement of the power piston.

Low Temperature Stirling Engine

5

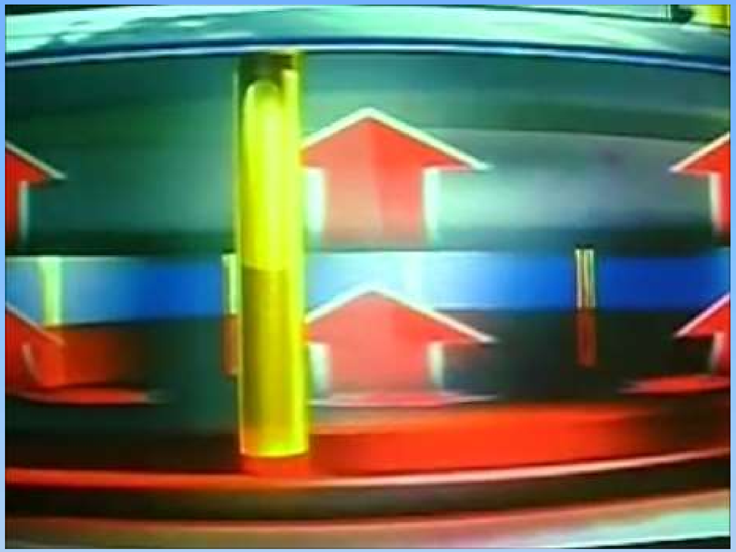
Procedure:

The Stirling engine is placed on top of a cup with hot water. After waiting for a short while, the flywheel is gently pushed.



https://www.youtube.com/watch?v=qJvCbiwnPNM

Low Temperature Stirling Engine



When the bottom plate is heated, the air in the main chamber expands. As a result, the power piston is pushed upwards. The flywheel is set in motion with a gentle push. It additionally supports the motion. A second piston is connected to the wheel, the so-called displacer disk. It pushes the air inside alternately down and up again. Thus, the air is alternately heated and cooled again meaning it expands and contracts again. The cycle is closed and the engine is running.

Low Temperature Stirling Engine

Principle of the engine (3D animation)

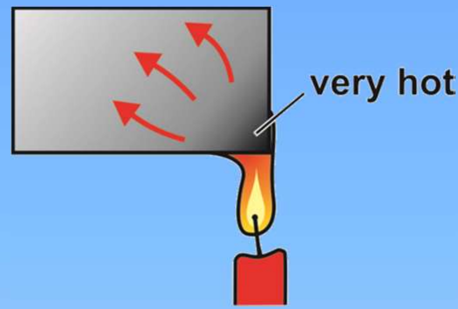
(Clip from the German Infotainment Show „Galileo“)

https://www.youtube.com/watch?v=76eneqAO9RA&t=0s
(part from 0:49 on)

6. Entropy Conduction

Entropy Conduction

Entropy tends to *spread*.
If two differently warm objects touch each other, entropy will flow from the warmer object to the cooler one.



Gases and foam materials strongly hinder the flow of entropy. This property is, for example, used in picnic coolers to keep food and beverages cold.

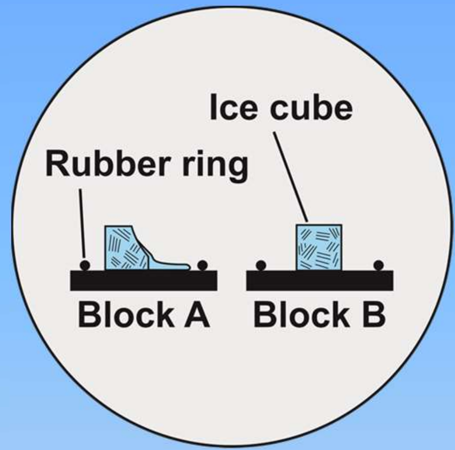
Metals, however, are good entropy conductors with an entropy conductivity that is about 1000 times higher than that of gases and foam materials. Therefore, they are used to transfer entropy over a short distance.

Ice Melting Blocks

6

Procedure:

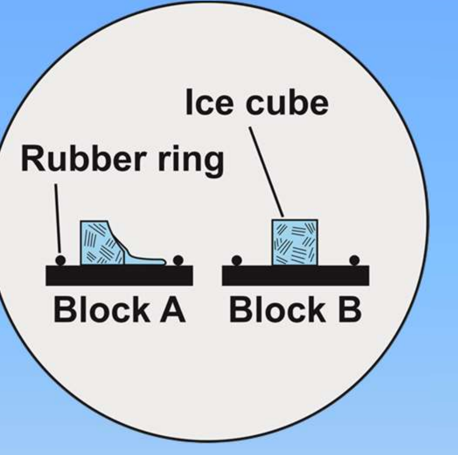
Both blocks have room temperature. Nonetheless, one feels cool whereas the other feels warm. Then, an ice cube is placed in the middle of each block.

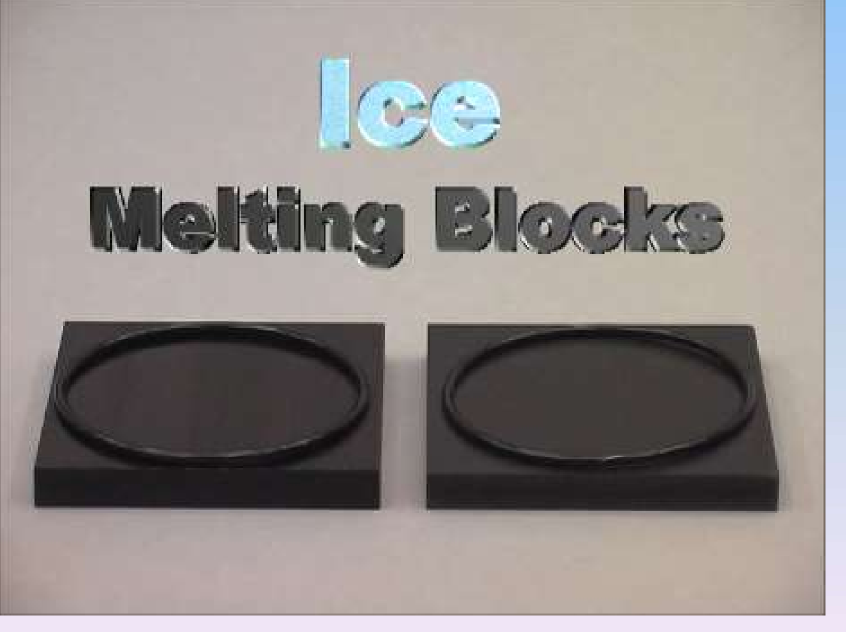


Ice Melting Blocks

Procedure:

Both blocks have room temperature. Nonetheless, one feels cool whereas the other feels warm. Then, an ice cube is placed in the middle of each block.



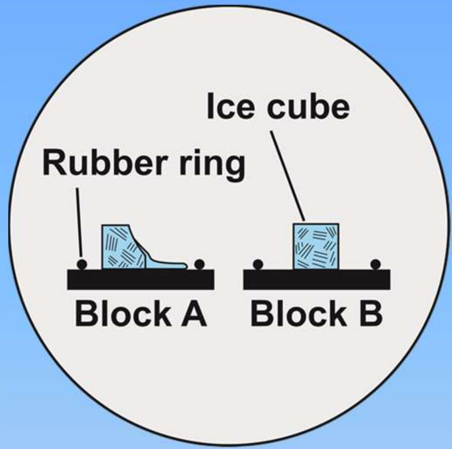


https://www.job-stiftung.de/index.php?experiment-3.a-ice-melting

Ice Melting Blocks

Procedure:

Both blocks have room temperature. Nonetheless, one feels cool whereas the other feels warm. Then, an ice cube is placed in the middle of each block.



Observation:

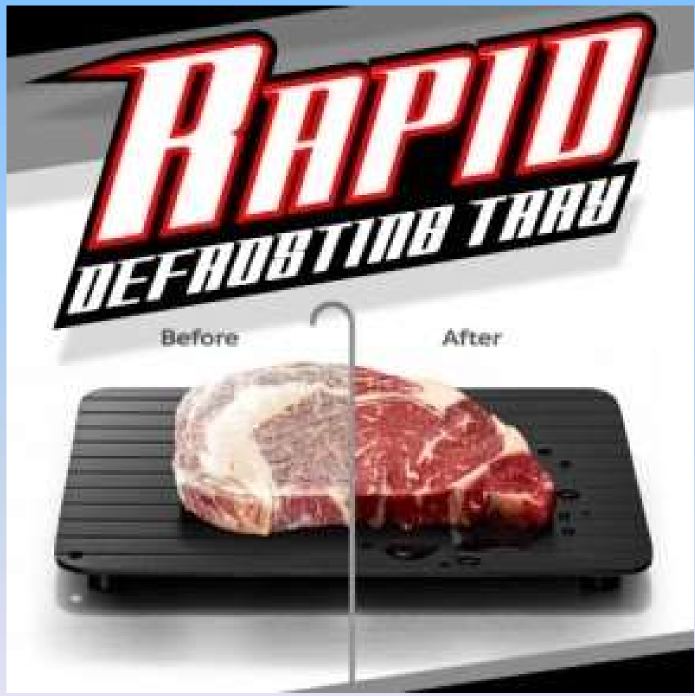
The ice on block A (which feels cool) melts much faster.

Explanation:

Block A is made of aluminum, block B, however, of high density foam. Aluminum is a very good entropy conductor, high density foam a very bad one. The entropy flow by conduction always takes place in the direction of a temperature drop. Therefore, the (warmer) metal transfers entropy to the (colder) ice, which begins to melt as a result. The metal block feels cool at the beginning for the same reason.

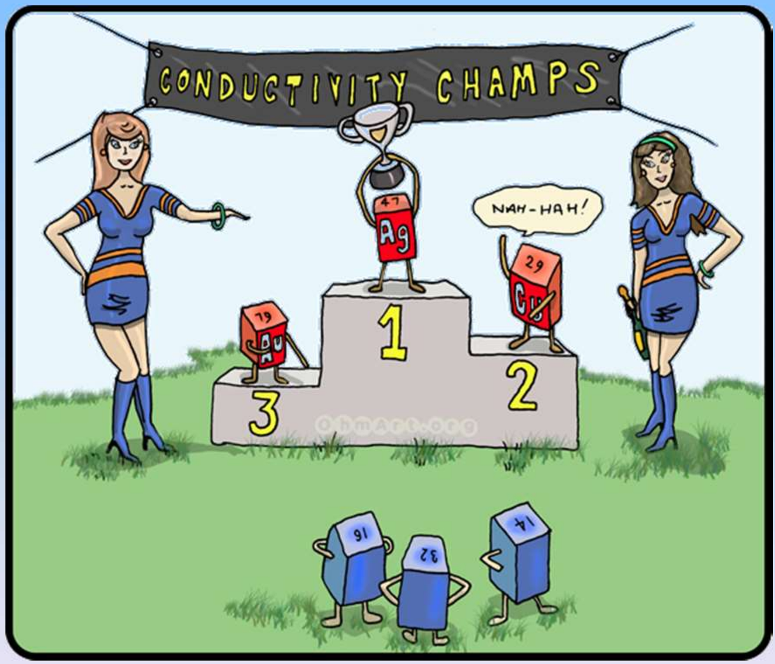
Rapid Defrosting Trays

The same principle is used by the so-called “rapid defrosting trays” for frozen food such as meat.



Entropy Conduction in Metals

But there are also differences between the values of entropy conductivity of various metals.

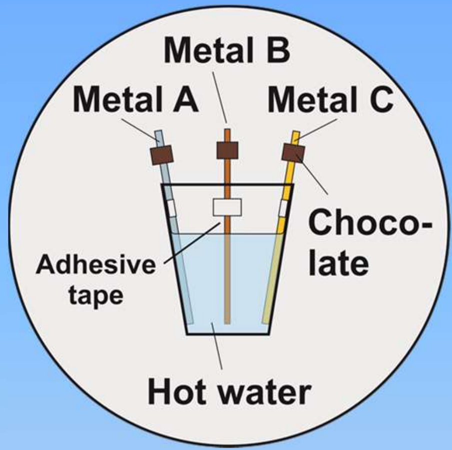


Entropy Conduction in Metals

7

Procedure:

Each piece of chocolate is skewered with one of the three thin rods made of different metals. The rods are taped to the inside edge of a cup. Then, the cup is filled with hot water.

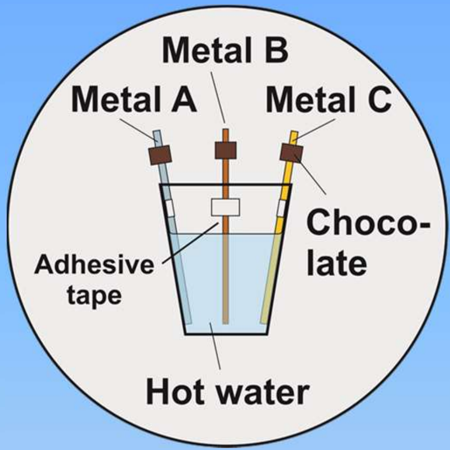


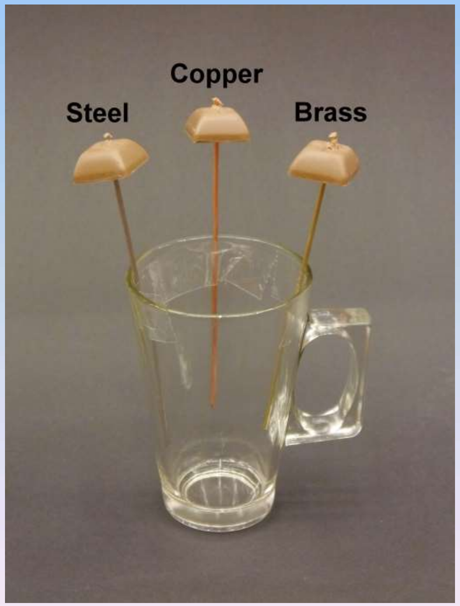
Entropy Conduction in Metals

7

Procedure:

Each piece of chocolate is skewered with one of the three thin rods made of different metals. The rods are taped to the inside edge of a cup. Then, the cup is filled with hot water.

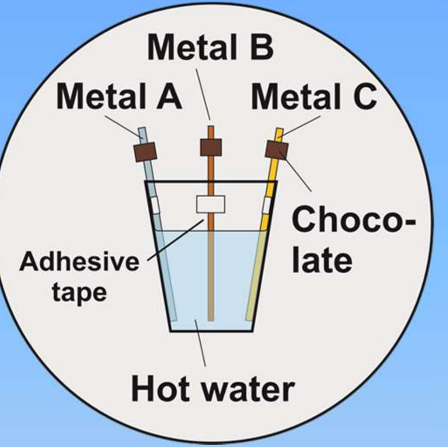




Entropy Conduction in Metals

Procedure:

Each piece of chocolate is skewered with one of the three thin rods made of different metals. The rods are taped to the inside edge of a cup. Then, the cup is filled with hot water.



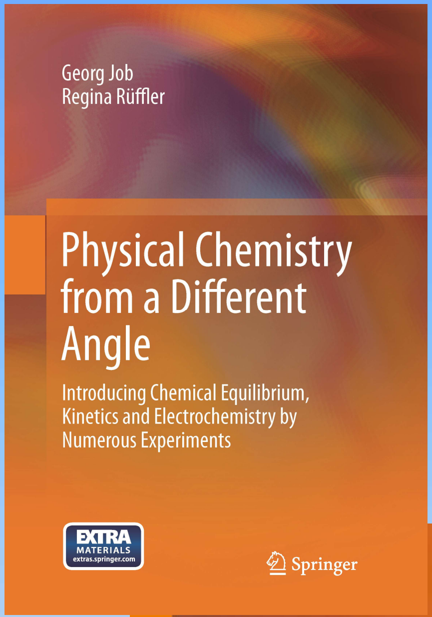
Observation:

After a while, two of the pieces of chocolate slide down in the direction of the water one after another.

Explanation:

First, the piece of chocolate in contact with metal B (copper) slides down, then follows the one in contact with metal C (brass). The piece in contact with metal A (steel), however, does not slide down. This sequence reflects the different entropy conductivities of the metals with the highest value for copper.

7. Outlook

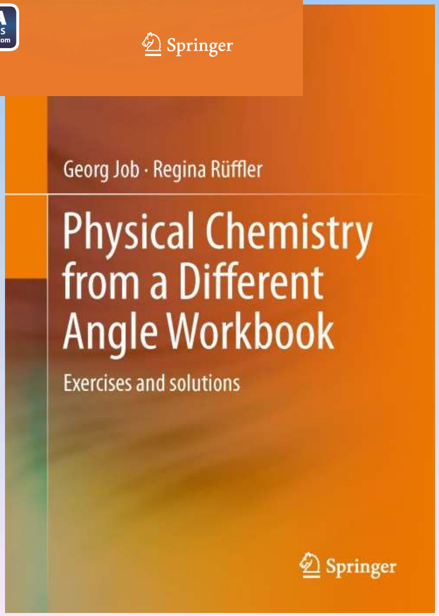


Georg Job, Regina Rüffler

Physical Chemistry from a Different Angle

An introduction with new concept and numerous experiments

ISBN 978-3-319-15665-1



Georg Job, Regina Rüffler

Physical Chemistry from a Different Angle Workbook

Collection of exercises with detailed solutions to accompany the textbook

ISBN 978-3-030-28490-9

Further information

(PowerPoint presentations, instructions for the experiments, videos etc.):

www.job-foundation.org

and facebook presence

@JobFoundationPhysChem