to the workshop

"Teaching Entropy with Fun"

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Heating of Metal by Forging

**Equipment:**
- anvil
- heavy sledgehammer
- soft annealed piece of copper (having a volume of a few cubic centimeters) with handle

**Chemicals:**
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**Safety:**
Because hammers are notorious for causing thumb and finger injuries one should be very careful and wear protective gloves when working with this tool.

**Procedure:**
The piece of copper is put on the anvil and hit forcefully about 20 times with the sledgehammer.

**Observation:**
The piece of copper becomes so hot that it hisses when put into water.

**Explanation:**
The atomic structure of the copper is permanently disturbed by hitting it with the hammer. As main effect of the entropy generated during the process the piece of copper becomes hot.

**Disposal:**
The piece of copper can be reused after annealing and quenching in water.

**Supplement:**
In the entertainment television show “Wanna bet, that ... ?”, which was very popular in Germany, the blacksmith Torsten Becker made the bet that he together with four colleagues could heat a piece of iron with strong hits with heavy hammers to such an extent that it would be possible to prepare a fried egg on it. And he won the bet!
Expansion of a Wire Caused by Electric Current

**Equipment:**
- Power supply e.g. 25 V, 10 A
- Two isolating supports
- Resistance wire (thin)
  - E.g. constantan wire (600 × 0.4 mm Ø)
- Weight (10 to 20 g) e.g. big nut or hook weight
- Two cables
- “Height indicator” e.g. glass rod in a stopper with a hole

**Chemicals**

**Safety:**
The wire should not be touched as long as the current flows through it.

**Procedure:**
**Preparation:** The thin wire is stretched between the two isolating supports the weight being located in the middle of the wire. The “height indicator” is placed below the weight. Subsequently, each of the isolating supports is connected by one of the cables with the power supply.
- **Procedure:** First, the current is slowly increased. Subsequently, the current is decreased again.

**Observation:**
The weight in the middle of the wire 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. The movement of the weight can be observed especially clearly with the help of shadows created by a lamp.

**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. The effect can be easily observed by the lowering of the weight. If the electric current is decreased again, also the entropy generated in the wire decreases; the wire gradually cools down and shrinks again.

**Disposal:**

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**Bimetallic Jumping Disc**

**Equipment:**
bimetallic jumping disc
(optional: cup with warm water)

**Chemicals:**
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**Safety:**
It is recommended to wear safety glasses.

**Procedure:**
First, the disc is warmed to about body temperature by rubbing it between the palm of one hand and the fingers of the other or by holding it, for example, against the outside of a cup with warm water. Then, it is “clicked” from its original convex shape to a concave shape. If the metal was warm enough, the disc will remain temporarily in this “inverted” position. Subsequently, the disc is quickly but carefully placed on a hard surface like a 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, which are welded together (so-called “bimetal”). When the entropy of the disc is increased, the two metals expand varying strong because of their rather different coefficients of thermal expansion and above a temperature of approximately 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 same principle applies to a thermostat or a shunt-valve in a car.

**Disposal:**
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**Source of supply:**
for example Educational Innovations (http://www.teachersource.com)
Compression and Expansion of Air

**Equipment:**
plexiglass cylinder with piston sealed with O-ring and with implemented thermocouple chart recorder
two cables

**Chemicals:**
silicone grease

**Safety:**
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**Procedure:**
The piston is greased with a small amount of silicone grease and then wiped off. The electric connections of the thermocouple are connected to the chart recorder using the cables. Subsequently, the zero position of the chart recorder is adjusted to the center of the paper (50 %). Then, the piston is quickly pressed into the air-filled cylinder. The piston is held down until the chart recorder deflection has returned to its original value. Subsequently, the piston is released. The measuring range of the recorder has to be chosen according to the thermocouple used, the paper advance should be about 100 mm/min.

**Observation:**
The compression is characterized by an increase in temperature, the expansion, however, by a decrease in temperature.

**Explanation:**
If air is compressed, the atoms become accelerated, the disorder and therefore the entropy increases and as a result the gas becomes warmer (phase 1). After a while, the gas cools down to its original value 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 further cooling (phase 3). Then, entropy begins to flow back from the environment into the system and the gas begins to warm up (phase 4). The more slowly this is done, the more the difference between compression and expansion disappears.

**Disposal:**
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**Ice Calorimeter**

**Equipment:**
- double-walled calorimetric vessel
- large test tube
- graduated cylinder calibrated in the unit of entropy (0.82 mL of melt water corresponds to an entropy of 1 J/K)
- thermometer
- mortar and pestle
- sparkler
- ring stand with clamp

**Chemicals:**
- iron powder
- sulfur powder
- crushed ice

**Safety:**
- sulfur powder (S):
  - H315
  - P302+352
- iron sulfide (FeS):
  - H400
  - P273

Because of the generation of sulfur containing fumes during the reaction it is obligatory to work in a fume hood. It is also required to wear safety glasses and protective gloves.

**Procedure:**
Iron powder and sulfur powder are cautiously mixed in a mortar at a the molar ratio of 1:1. 22.0 g of the mixture (which corresponds to 1/4 mol FeS) are put into the test tube. Subsequently, the test tube and the thermometer (in the case of an electronic thermometer its temperature sensor) are placed in the calorimetric vessel filled with crushed ice. Before the reaction is started the stopcock of the vessel is opened to remove the water, which was produced in the meantime. Then, the stopcock is closed, the reaction of the Fe-S mixture is initiated with the help of a sparkler and the stopcock is opened again. The melt water produced during the reaction is collected in the graduated cylinder.

**Observation:**
The mixture reacts thereby glowing red. Additionally, sulfur containing fumes are generated. Part of the ice melts. The temperature in the calorimeter remains (almost) constant.
**Explanation:**
Iron reacts with sulfur to iron sulfide:

\[ \text{Fe} + \text{S} \rightarrow \text{FeS} \]

During the reaction a considerable amount of entropy is released. 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, i.e. 1 J/K).

**Disposal:**
The iron sulfide residue is collected in a special container for inorganic solids, which is subsequently sent for proper disposal.
Fire Piston

**Equipment:**
fire piston consisting of lower piston, cylinder and upper piston
tweezer

**Chemicals:**
tinder e.g. cotton wool

**Safety:**
It is recommended to wear safety glasses.

**Procedure:**
A small piece of tinder e.g. cotton wool is poked with the aid of a tweezer into the hole in the lower piston (the tinder should be teased apart so that the fibers are well separated). Subsequently, the cylinder is placed on the lower piston and the upper piston is pushed a few centimeters into the cylinder. Then, the upper piston is forced vigorously down (the cylinder should not be tilted, otherwise it may break).

**Observation:**
The piece of 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.
The same principle is utilized in diesel engines to ignite the fuel-air mixture in the cylinders of the engine.

**Disposal:**
The singed cotton wool can be discarded as household waste.
Temperature as Function of Time in Expanding Rubber

**Equipment**
rubber band (e.g. 3 x 20 x 50 mm)  
with thermocouple  
chart recorder  
two cables

**Chemicals:**

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**Safety:**
It is recommended to wear safety glasses. One should make sure that the rubber band does not tear or snap back.

**Procedure**
First, the thermocouple is connected to the chart recorder using the cables. Subsequently, the zero position of the chart recorder is adjusted to the center of the paper (50 %) and the rubber band is expanded and then relaxed several times. The measuring range has to be chosen according to the thermocouple used, the paper advance should be about 250 mm/min.

**Observation:**
During expansion the temperature rises whereas the temperature sinks again when the rubber band is allowed to contract. This temperature change can be observed no matter how often the experiment is repeated. The plot of $T$ against $t$ resembles a square wave.

**Explanation:**
The effect of increasing entropy on rubber is different to that on most substances: Whereas solids, liquids and gases usually expand with rising temperature, rubber contracts when heated. Inversely, a substance such as rubber that contracts when entropy is added to it will become warmer when expanded. When the rubber is allowed to contract exactly the opposite will happen. Therefore, a rubber band that is expanded and then relaxed, will become warm at first and then cold again. The energy expended at the beginning is retrievable. The process is reversible. Entropy is scarcely generated because the band is exactly as cool at the end as it was at the beginning.

The unusual behavior of rubber is caused by its molecular structure. Rubber consists of very long chains of polymerized molecules. The random-length chains are held together by weak intermolecular forces but are also joined at irregular intervals by covalent disulfide bonds (crosslinks). The crosslinks produced by vulcanization prevents the polymer chains...
from moving independently (such as, for example, the individual noodles in a heap of spaghetti would do). In the unstressed state, the chains are folded and 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. The experiment demonstrates the entropic character of rubber elasticity.

**Supplement:**

The experiment can be adapted in a simplified manner to everyday life: One touches a broad rubber band with the upper lip, which is very sensitive to changes in temperature and after waiting a short while for equalization of temperature, the band is stretched quickly and powerfully and immediately pressed again against the upper lip. It feels noticeably warm. When the stretched band is allowed to contract to its original length and then quickly pressed against the upper lip there is a noticeable cooling.

**Disposal:**
**Pop-pop Steam Boat**

**Equipment:**
- pop-pop boat
- big bowl, washtub, small pool or the like
- candle
- matches or lighter
- plastic dropper

**“Chemicals”:**
- water

**Safety:**
The precautions usual in everyday life for handling burning candles have to be observed. Since the boat will get hot, one should not touch it during or shortly after its operating.

**Procedure:**
Using the plastic dropper, water is filled into one of the exhaust pipes of the boat until it flows out of the second pipe. The boat is put carefully into the water in a bowl (or the like) making sure that the water stays in the boiler and both exhaust pipes are under the water. The candle is placed into the holder and the wick is lighted. Subsequently, the holder is gently 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 without moving parts. The candle heats the water in the boiler. When the water boils it creates a brief burst of wet steam (a mixture of hot water and steam), which is expelled through the pipes in the rear of the boat and the boat moves forward in response to the jet of wet steam (phase 1). Upon leaving the boiler, some of the steam condenses in the cooler part of the pipes thereby creating a partial vacuum, which refills the pipes and boiler with water (phase 2). The cycle can begin again.

The boiler consists of a small metal pan whose top is a slightly convex piece of very thin, springy metal that flexes with the expanding and contracting steam. The resulting rattle gives the pop-pop boat its name.

**Disposal:**
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Low Temperature Stirling Engine

**Equipment:**
- Stirling engine
- cup or mug
- electric water kettle (or the like)
  (optional: small bowl)

**“Chemicals”:**
- water
  (optional: crushed ice)

**Safety:**
The precautions usual in everyday life for handling hot water have to be observed.

**Procedure:**
Hot water (< 100 °C) is filled in a cup. Subsequently, the Stirling engine is placed on top of the cup. After waiting for about 2 minutes in order for the bottom plate to warm up, the flywheel is gently pushed.
Alternatively, the engine can be put on a small bowl filled to the brim with ice.

**Observation:**
The Stirling engine runs as long as the water in the cup is warm enough. If one takes it off the cup, it will stop after a short while.

**Explanation:**
Stirling engines such as the beta type with only one cylinder presented here operate with a temperature difference between the plates. While the bottom plate is heated by the hot water in the cup, the top plate remains at room temperature. With the large displacer disk (made of Styrodur etc.) at the top, most of the air inside the main chamber is at the bottom, where it is heated by the warm bottom plate. Due to the heating, the gas expands and pushes the small power piston upwards, which drives the flywheel via a connecting rod and a crankshaft. This movement acts in turn on the displacer disk via a second connecting rod with a 90 degree offset between the piston and the displacer disk. The displacer disk moves down to the bottom of the chamber while the air flows around the outside of the displacer disk to the top of the chamber where it is cooled by the top plate. Due to the cooling down, the gas contracts thereby causing the power piston to move downwards. This movement drives the flywheel a bit further. The cycle is closed.
The Stirling engine can also be operated by cooling the bottom plate. This can be done by placing it on a small bowl filled to the brim with ice. In this case, the flywheel rotates in the opposite direction.

**Disposal:**
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Ice Melting Blocks

**Equipment:**
- square aluminum block (painted black)
- square high density foam block of the same size (painted black)
- two rubber O-rings

**“Chemicals”:**
- crushed ice or ice cubes

**Safety:**
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**Procedure:**
Both blocks have the same temperature (room temperature). Nonetheless, the aluminum block feels cool whereas the foam block feels warm. The O-rings are put on the blocks and subsequently, a little bit of crushed ice or an ice cube is placed in the middle of each block.

**Observation:**
The ice on the aluminum block melts much faster.

**Explanation:**
Aluminum as a metal is a very good entropy conductor, high density foam, however, a very bad one. The entropy flow by conduction always takes place in the direction of a temperature drop. Therefore, the (warmer) aluminum transfers entropy to the (colder) ice, which begins to melt as a result. The aluminum block feels cool at the beginning for the same reason. Entropy flows from the (compared to room temperature) warmer hand to the aluminum block. This loss of entropy makes the skin feel cooler. However, the high density foam as a bad entropy conductor transfers nearly no entropy.
The O-rings on the blocks should prevent the water from flowing off.
The same principle is used by the so-called “fast defrosting trays” for frozen food such as meat.

**Disposal:**
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Entropy Conduction in Metals

**Equipment:**
cross or star made of rods with equal length and diameter of different metals (e.g. copper, brass, steel) connected with an additional rod, which is used for fixation
Bunsen burner
ring stand and clamp
(optional: small steel balls)

**Chemicals:**
wax

**Procedure:**
The cross (or star) is attached in such a way to the ring stand that the hub is above the burner. Wax spheres are stuck to the ends of the rods (or small steel balls by means of wax). Subsequently, the burner is lighted.

**Observation:**
The wax spheres (or steel balls) fall off one after another: first the one connected with copper rod, then the one connected with the brass rod and finally the one connected with the steel rod.

**Explanation:**
The sequence of the falling spheres reflects the different entropy conductivity $\sigma_S$ of the metals.
Because the spheres fall down when the melting temperature of wax is reached the experiment rather show the temperature conductivity (thermal diffusity) $a = \sigma_S/(\rho \times c)$. The product of the density $\rho$ and the specific entropy capacity $c$ is, however, very similar for the different metals, which is why the result essentially only depend from the entropy conductivity.

**Supplement:**
In a simplified version of the experiment each of three pieces of chocolate is skewered with one of the thin rods (e.g. about 135 mm long, about 2 mm $\varnothing$) made of copper, brass and steel. The rods are then taped to the inside edge of a cup (the use of a well-adhering fabric tape is recommended). Subsequently, the cup is filled with hot water so that the rods at least are half covered. After a short while (less than 30 s), the piece of chocolate in contact with the copper rod slides down in the direction of the water. Subsequently (after about 90 s), the one in contact with the brass rod follows. The piece in contact with the steel rod,
however, does not slide down. For the experiment, milk chocolate should be used because of its lower melting point (compared to dark chocolate).

**Disposal:**

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