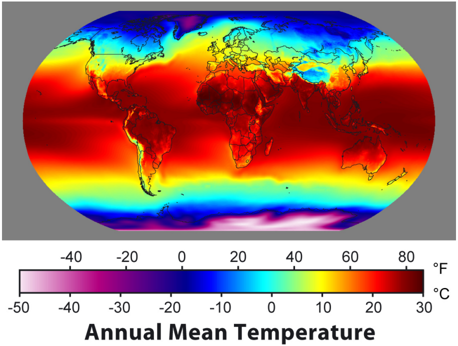
Chapter 1 - Temperature and Heat



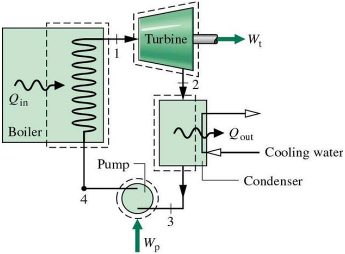
"It doesn't make a difference what temperature a room is, it's always room temperature."

-Steven Wright

David J. Starling
Penn State Hazleton
Fall 2013

Temperature

Thermodynamics is the study of thermal (or internal) energy of systems.



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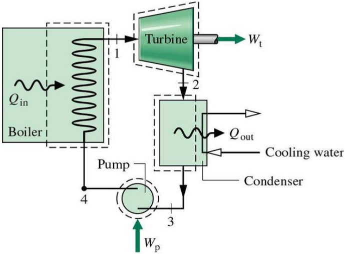
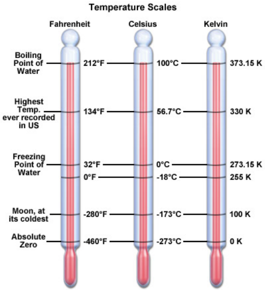


Engines are described using the concepts of thermodynamics, such as heat and temperature.

Temperature

Temperature is a characterization of the average thermal energy of a substance which correlates to the concepts of hot (more E) and cold (less E).



Temperature	°C	°F
Boiling point of water[a]	100	212
Normal body temperature	37.0	98.6
Accepted comfort level	20	68
Freezing point of water[a]	0	32
Zero of Fahrenheit scale	≈ −18	0
Scales coincide	−40	−40

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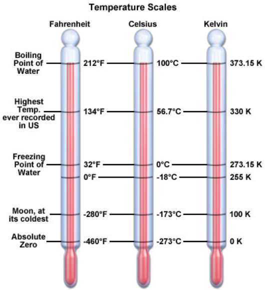

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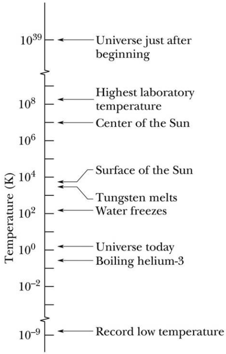
The temperature of an object determines how it behaves (e.g., solid, liquid, gas).

Temperature

Temperature can be measured in many ways; in physics, we use the kelvin scale.



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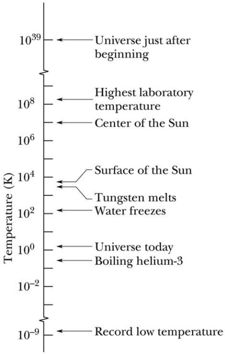
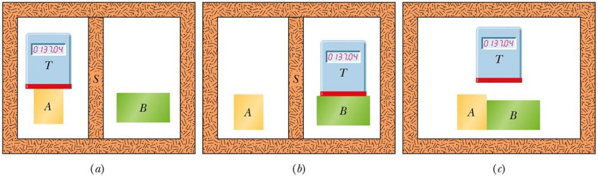


To go from kelvin to degrees Celsius, $T_C = T - 273.15°$.
To go from degrees Celsius to degrees Fahrenheit, $T_F = \frac{9}{5}T_C + 32°$.

Temperature

The Zeroth Law of Thermodynamics: Two bodies are in thermal equilibrium if and only if they have the same temperature.



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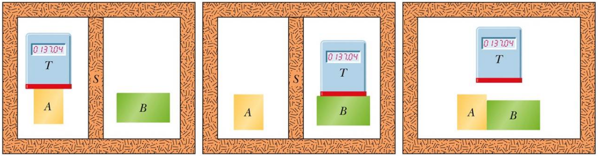
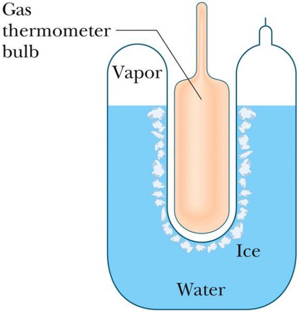


(a) (b) (c)

To measure the temperature of a body, we need to put it in thermal contact with a temperature meter.

Temperature

Temperature is defined using two universal points: the triple point of water (273.16 K, 611.73 Pa) and absolute zero (0 K, 0 Pa).



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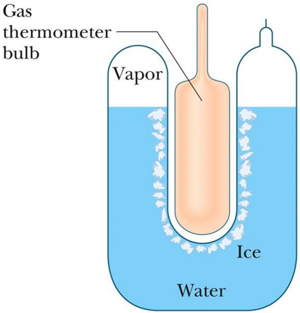
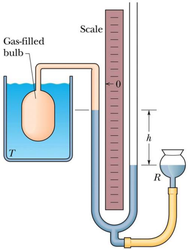


The triple point is the pressure and temperature at which water exists as a gas, liquid *and* solid simultaneously.

Temperature

A constant-volume gas thermometer uses a gas-filled bulb of unknown temperature along with a mercury manometer.



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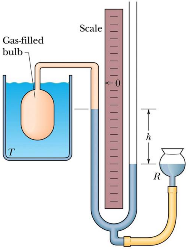

We can now relate the pressure in the bulb to its temperature using an unknown constant: $T = Cp$.

Temperature

If we also measure at the triple point (for reference), we get $T_3 = Cp_3$. Taking the ratio:

$$\begin{aligned} \frac{T}{T_3} &= \frac{p}{p_3} \\ T &= T_3\left(\frac{p}{p_3}\right) \\ &= 273.16\left(\frac{p}{p_3}\right) \end{aligned}$$

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- How can we remove the effect of the gas?

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- Unfortunately, this result is *gas dependent*.
- How can we remove the effect of the gas?

$$T = 273.16 \lim_{gas \to 0}\left(\frac{p}{p_3}\right)$$

Temperature

Unsatisfied with the Celsius and Kelvin temperature scales, you decide to create your own. On your temperature scale, the ice point is 0.0°M and the steam point is at 366.1°M, where “M” stands for “my scale.” What temperature on your scale corresponds to 0 K?

(a) -273.1°M

(b) -500.0°M

(c) -1000.0°M

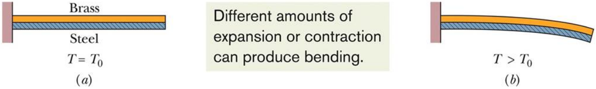
(d) -732.4°M

(e) -633.9°M

Thermal Expansion

We know that gases expand when heated—but so do solids!

$$\Delta L = L\alpha\,\Delta T$$



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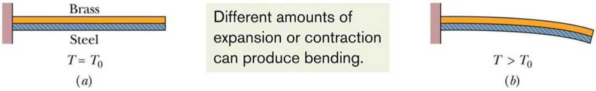
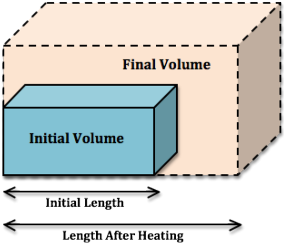


Each solid has a unique **linear expansion coefficient** α; i.e., different metals expand different amounts for the same temperature change.

Thermal Expansion

For liquids and solids, we consider their volume:

$$\Delta V = V\beta\,\Delta T$$



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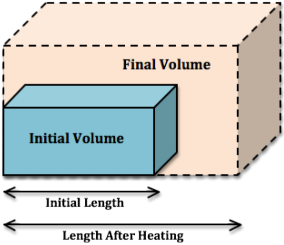


Here, $\beta = 3\alpha$ is the **volume expansion coefficient**.

Thermal Expansion

The length of an aluminum pendulum in a certain clock is 0.2480 m on a day when the temperature is 23.30°C. This length was chosen so that the period of the pendulum is exactly 1.000 s. The clock is then hung on a wall where the temperature is -5.00°C and set to the correct local time. Assuming the acceleration due to gravity is the same at both locations, by how much time is the clock incorrect after one day at this temperature?

(a) 69.3 s

(b) 115 s

(c) 87.2 s

(d) 31.0 s

(e) 11.5 s

Thermal Expansion

An artist wishes to insert a gold pin into a hole in an iron sculpture and have it held permanently. The pin is slightly larger than the hole. The coefficient of linear thermal expansion of gold is slightly larger than that of iron. Consider the following options:

(a) increase the temperature of the pin and the sculpture by the same amount;

(b) decrease the temperature of the pin and the sculpture by the same amount;

(c) increase the temperature of the pin and decrease the temperature of the sculpture;

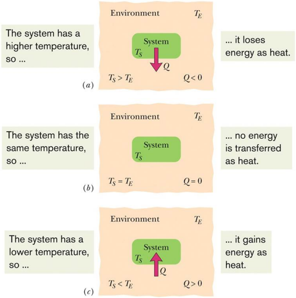
(d) decrease the temperature of the pin and increase the temperature of the sculpture;

(e) none of the above.

Which of the choices would most likely accomplish the artist's task?

Absorption of Heat

Heat Q is energy measured in joules (J) that is transferred between two objects due to a temperature difference.



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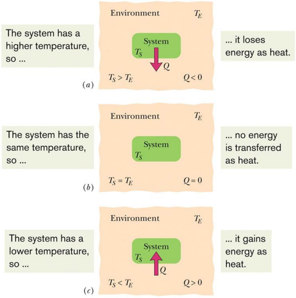

An object doest not *contain* heat; instead, energy is transferred as heat.

Absorption of Heat

Energy always flows from hot to cold.

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Heat is also measured in calories (cal), kilocalories (kcal or Cal) and British thermal units (Btu):

$$1 \text{ cal} = 3.968 \times 10^{-3} \text{ Btu} = 4.1868 \text{ J}$$

Absorption of Heat

When heat is absorbed by an object, its temperature increases linearly. The proportionality is called **heat capacity** C.

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Heat capacity depends on the material, but also on its mass:

$$C = cm \to c = C/m = \frac{Q}{m\,\Delta T}$$

We call c the specific heat of the material, with units of J/kg-K or cal/g-K.

Absorption of Heat

In this way, specific heat is more general and can be tabulated for different substances.

Substance	Specific Heat $\frac{\text{cal}}{\text{g}\cdot\text{K}}$	Specific Heat $\frac{\text{J}}{\text{kg}\cdot\text{K}}$	Molar Specific Heat $\frac{\text{J}}{\text{mol}\cdot\text{K}}$
Elemental Solids			
Lead	0.0305	128	26.5
Tungsten	0.0321	134	24.8
Silver	0.0564	236	25.5
Copper	0.0923	386	24.5
Aluminum	0.215	900	24.4
Other Solids			
Brass	0.092	380	
Granite	0.19	790	
Glass	0.20	840	
Ice (−10°C)	0.530	2220	
Liquids			
Mercury	0.033	140	
Ethyl alcohol	0.58	2430	
Seawater	0.93	3900	
Water	1.00	4187	

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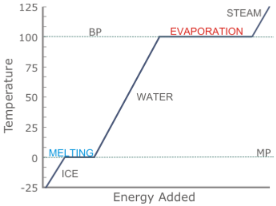
note: molar specific heat does not vary much, $\approx 8\%$

Absorption of Heat

When an object undergoes a phase change, heat is added to the system but the temperature remains fixed.



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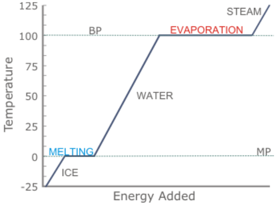


How much energy needs to be added to completely transform the material?

$$Q = Lm$$

L is the heat of transformation measured in J/kg.

Absorption of Heat

Why is water often used as a coolant in automobiles, other than the fact that it is abundant?

(a) Water expands very little as it is heated.

(b) The freezing temperature of water has a relatively large value.

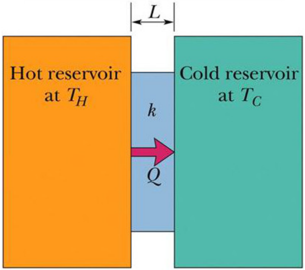
(c) The specific heat of water is relatively small and its temperature can be rapidly decreased.

(d) The specific heat of water is relatively large and it can store a great deal of thermal energy.

(e) Water does not easily change into a gas.

Heat Transfer Mechanisms

Conduction is the transfer of energy via direct contact of two objects at different temperatures.



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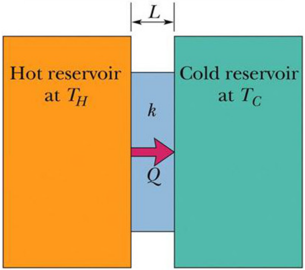

Here, the object (blue) has energy flowing through it at a steady rate.

Heat Transfer Mechanisms

Empirical determination of the energy transfer rate shows a dependence on surface area and material:

$$P_{cond} = \frac{Q}{t} = kA\frac{T_H - T_C}{L} \qquad (1)$$

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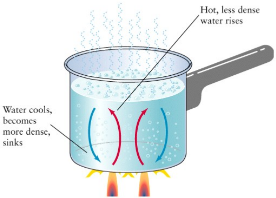
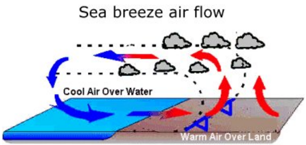
- k is the thermal conductivity of material
- A is the face area of the slab
- L is the thickness

Heat Transfer Mechanisms

Convection is the transfer of energy due to fluid in motion caused by a temperature gradient.





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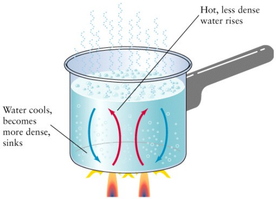
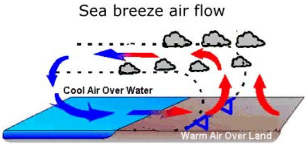


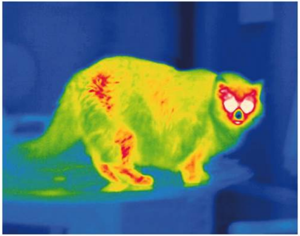


- atmospheric, winds
- ocean currents
- flames

Heat Transfer Mechanisms

Radiation is the transfer of energy via electromagnetic waves (visible light, infrared, x-rays, etc.). Warm objects glow and emit energy at a rate of:

$$P_{rad} = \sigma \epsilon A T^4 \qquad (2)$$



Edward Kinsman/Photo Researchers, Inc.

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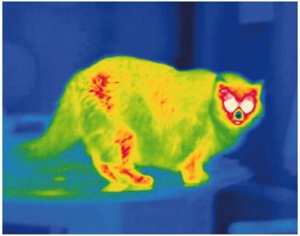

Edward Kinsman/Photo Researchers, Inc.

- $\sigma = 5.6704 \times 10^{-8}$ W/m^2-K^4 (Stefan-Boltzmann)
- ϵ is the emissivity of the object's surface
- A is the object's surface area

Heat Transfer Mechanisms

During the summer, sunlight warms the land beside a cool lake. This warming is followed by a breeze blowing from the direction of the lake toward the land. Why?

(a) Air naturally flows from cooler locations to warmer locations.

(b) The lake must be west of the land because winds typically blow from the west.

(c) The land is usually cooler near a lake, so this is a case of temperature inversion which causes air to blow from the direction of the lake.

(d) Warm air rises above the land and cooler air moves downward, appearing to come from the direction of the lake, but it is really from above the land.

(e) Warm air rises from above the land and is replaced by the air blowing in from the lake.