Temperature and Heat

Mechanics is based on fundamental concepts:

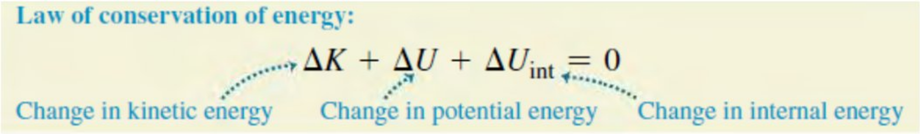
mass, energy, force, work, momentum, angular momentum,…

Thermal phenomena implicate specific concepts:

Temperature, Heat, Internal Energy, Work,…

the relationship of internal energy to temperature changes, heat, and work is the heart of the area of physics called thermodynamics.

- When a car with locked brakes skids to a stop, the tires and the road surface both become hotter.
- The energy associated with this change in the state of the materials is called internal energy.
- Raising the temperature of a body increases its internal energy; lowering the body's temperature decreases its internal energy.



Law of conservation of energy:

$$\Delta K + \Delta U + \Delta U_{\text{int}} = 0$$

Change in kinetic energy

Change in potential energy

Change in internal energy

Energy is never created or destroyed; it only changes form.

Principle of Carnot

Thermodynamics: part of the Physics dealing with the energy transformations involving heat, work and other aspects of energy and their correlation with the properties of the matter

1. Temperature and Thermal equilibrium

The concept of temperature is rooted in qualitative ideas based on our sense of touch.
A body that feels "*hot*" usually has a higher temperature than a similar body that feels "*cold*."

$\Rightarrow$ *Relative perception* (depend of reference body), only qualitative, submitted to errors
$\Rightarrow$ Many properties of matter that we can *measure* depend on temperature: the length of a metal rod, steam pressure in a boiler, the ability of a wire to conduct an electric current, and the colour of a very hot glowing object.

The temperature is related to the kinetic energies of the molecules of a material (microscopic definition). Here, we'll develop a *macroscopic* definition of temperature.

Understanding the concept of temperature requires definition of two other concepts:

- thermal contact
- thermal equilibrium

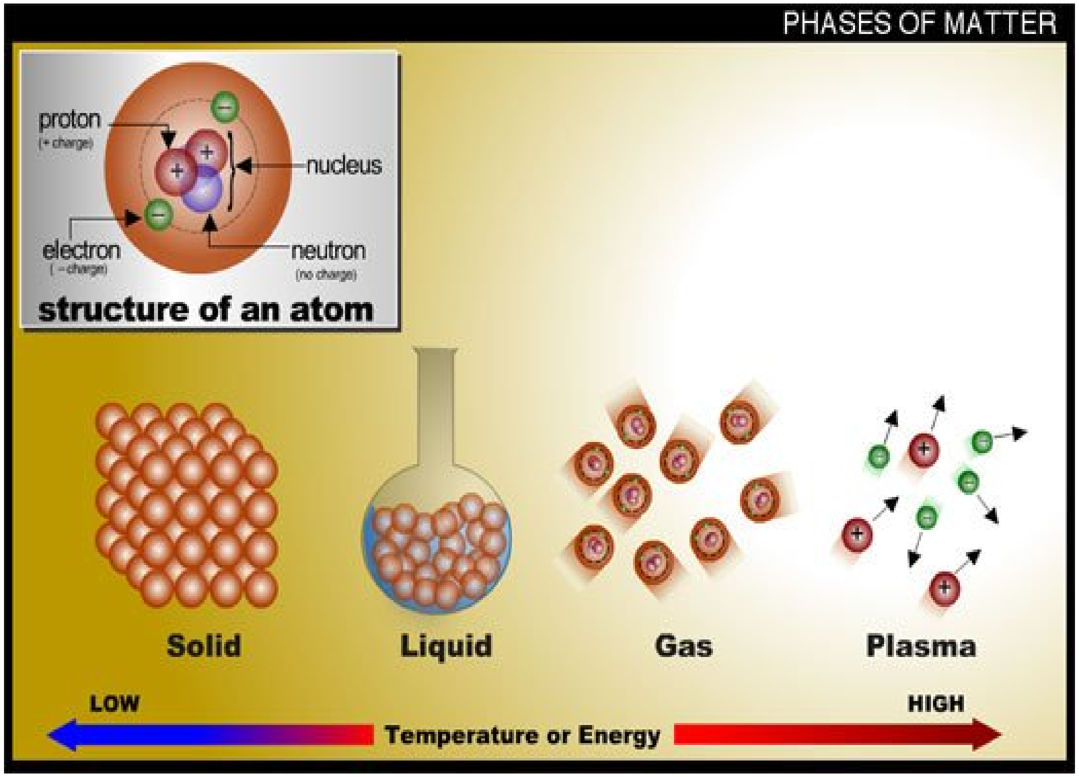
Thermal contact: Two systems are in thermal contact if between them an energy exchange can occur due to initial different temperatures of the systems

Thermal equilibrium: is the situation in which between two systems in thermal contact there is no energy exchange (heat or electromagnetic radiation). In this situation the temperature of the two systems is identical.

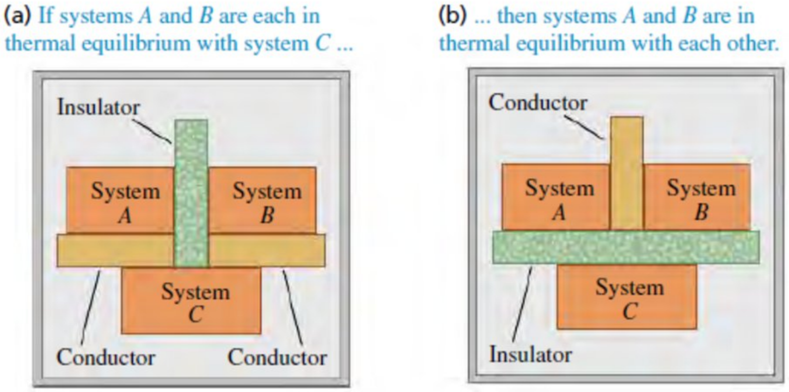
The Kinetic Theory of Matter

- All of the particles that make up matter are constantly in motion

- Solid= vibrating atoms
- Liquid= flowing atoms
- Gas= move freely
- Plasma= move incredibly fast and freely



2. The Zeroth law of Thermodynamics


(a) If systems *A* and *B* are each in thermal equilibrium with system *C* ...

(b) ... then systems *A* and *B* are in thermal equilibrium with each other.

suppose that system C is a thermometer

Two systems are in thermal equilibrium if and only if they have the same temperature.

A thermometer actually measures its own temperature, but when a thermometer is in thermal equilibrium with another body, the temperatures must be equal.

When the temperatures of two systems in thermal contact are different, they cannot be in thermal equilibrium => energy (heat) exchange to get the equilibrium (same T).

**Heat is a flow of energy
due to temperature
differences**

SCALES OF TEMPERATURE.

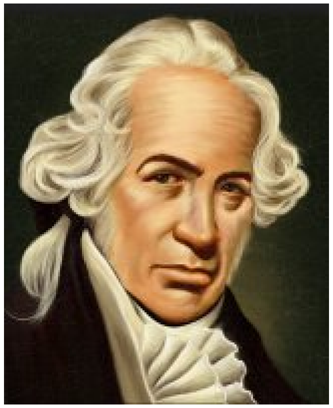
The zero principle makes possible to know if two systems have the same temperature or not, but is not assigning a value to a given temperature.
For this, it is necessary to define a scale of temperature.

(1) CELSIUS: boiling and freezing of water

By constructing a thermometer graduated from 0 to 100 in 1741, Anders Celsius chose to take as reference points the boiling and freezing temperatures of water. Note "° C" the "degree Celsius" (sometimes also called "centigrade degree ").

(2) FAHRENHEIT: ice-salt and human body

By building his alcohol and mercury thermometers in the early 18th century, Daniel Fahrenheit used a scale of 0 to 12 between the temperature of a mixture (half salt-half ice) for the "zero" and the temperature of the human body (for graduation 12). It is only then that he further divided each interval by 8 to reach the scale of 0 to 96 that we usually quote (8x12 = 96 ...). We then speak of "degree Fahrenheit", noted "° F".



still used in everyday life in the United States:
- the freezing temperature of water is 32F (thirty-two degrees Fahrenheit)
- the boiling temperature is 212F, both at standard atmospheric pressure.

$$T_F = \frac{9}{5} T_C + 32^\circ$$

$$T_C = \frac{5}{9}(T_F - 32^\circ)$$

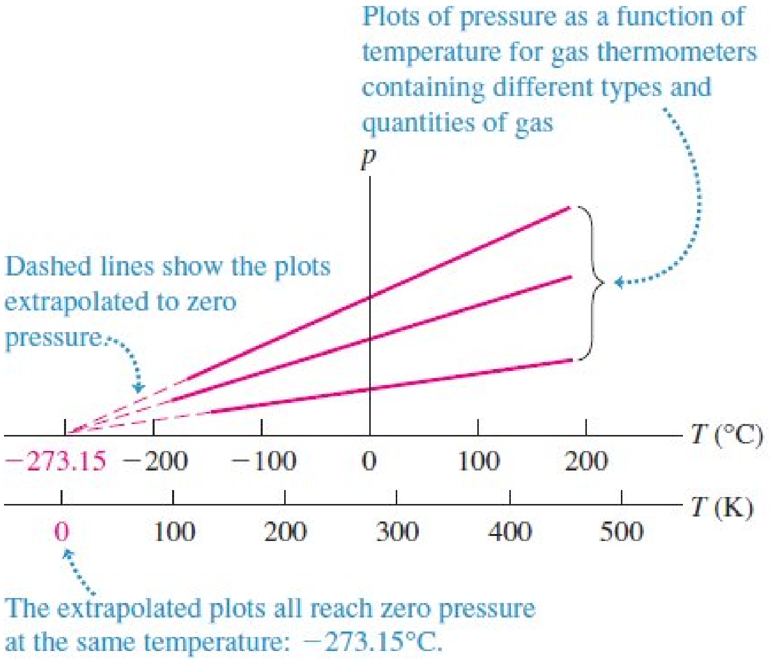
(3) Gas Thermometers and the KELVIN SCALE

- we would like to define a temperature scale that doesn't depend on the properties of a particular material.
- we'll discuss a thermometer that comes close to the ideal, the *gas thermometer.*

The principle of a gas thermometer is that the pressure of a gas at constant volume increases with temperature.

(a) A constant-volume gas thermometer

(b) Graphs of pressure versus temperature at constant volume for three different types and quantities of gas



! Same value for all gases

We use this extrapolated zero-pressure temperature as the basis for a temperature scale with its zero at this temperature. This is the Kelvin temperature scale, named for the British physicist Lord Kelvin (1824–1907).

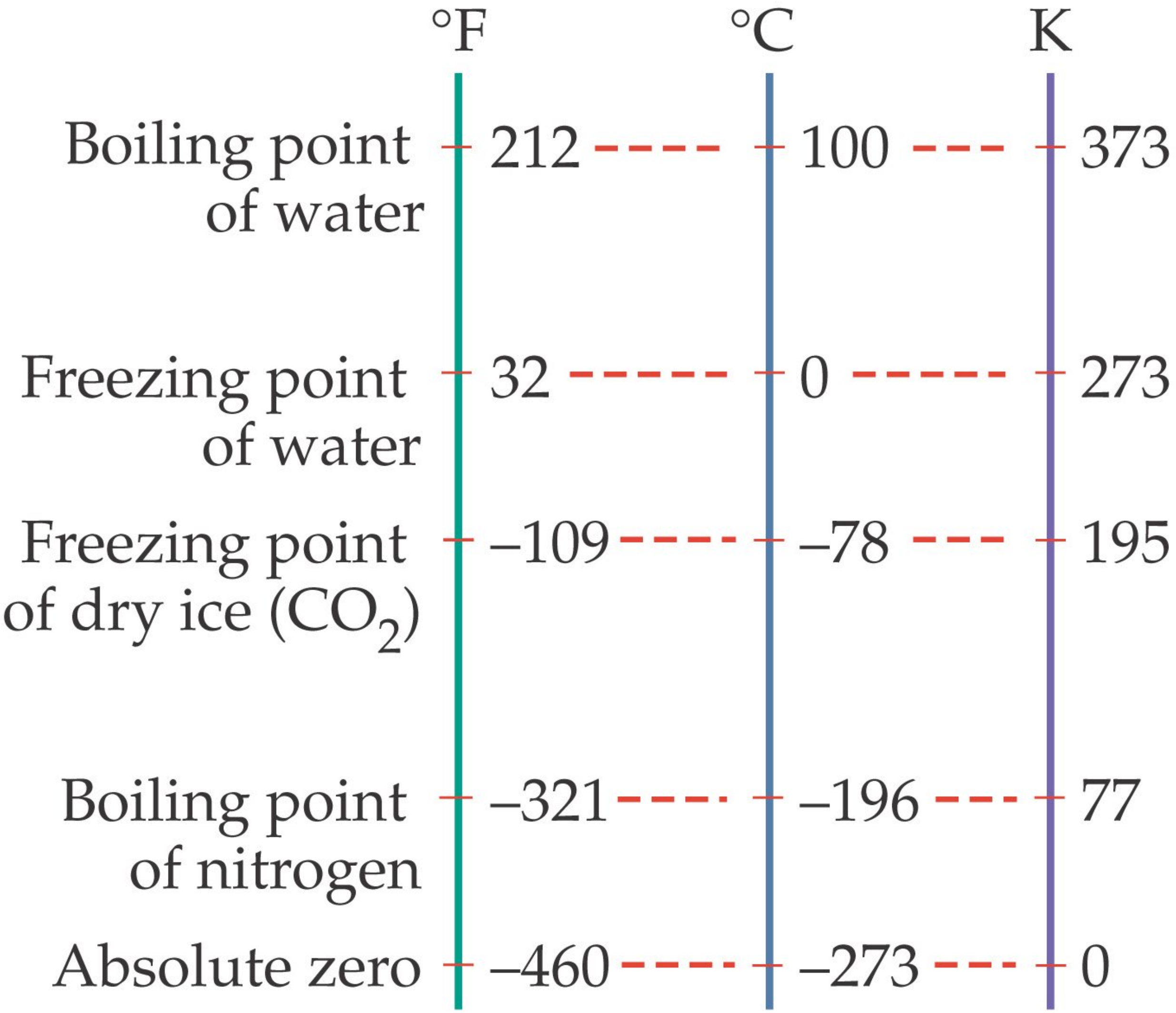
$$T_K = T_C + 273.15$$

Room temperature:20^oC
$=273.15+20=293.15K$

$T=-273.15^oC$ = OK absolute zero

a system of molecules (a gas, a liquid, or a solid) has its *minimum* possible total energy (kinetic plus potential);

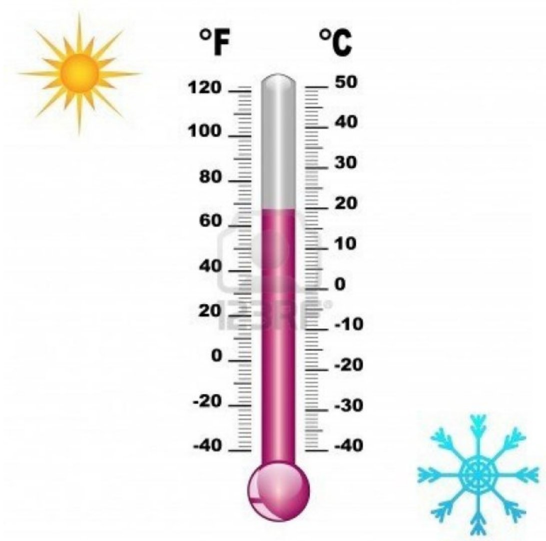
The three temperature scales compared:



MEASURING THE TEMPERATURE

- based on achieving thermal equilibrium between the measured body and the measuring instrument
- In thermodynamics, a thermostat is a closed system of constant temperature, which can be used to carry out heat transfers with a body placed in contact with it.

Different types of sensors



Dilatation
(solid, liquid, gas)

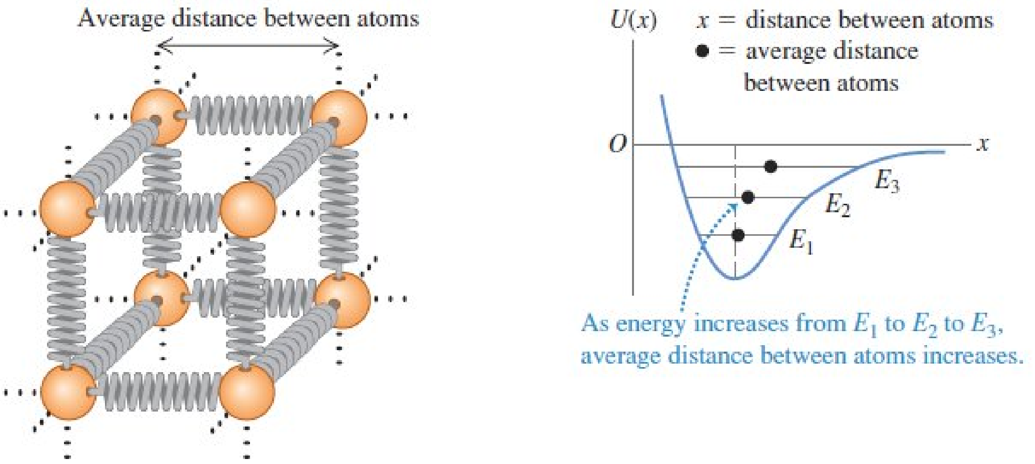
Optic (IR)

Thermistance

Thermocouple
(Seebeck effect)

Thermometers based on thermal expansion

Liquids, solids, gases



(a) A model of the forces between neighboring atoms in a solid

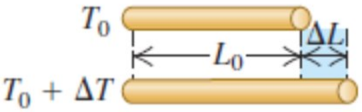
(b) A graph of the "spring" potential energy $U(x)$

As energy increases from E_1 to E_2 to E_3, average distance between atoms increases.

17.9 **(a)** We can model atoms in a solid as being held together by "springs" that are easier to stretch than to compress. **(b)** A graph of the "spring" potential energy $U(x)$ versus distance x between neighboring atoms is *not* symmetrical (compare Fig. 14.20b). As the energy increases and the atoms oscillate with greater amplitude, the average distance increases.

$$\Delta L = \alpha L_0 \, \Delta T \qquad \text{(linear thermal expansion)}$$

$$\Delta V = \beta V_0 \, \Delta T \qquad \text{(volume thermal expansion)}$$



Definition of Coefficient of Linear Expansion, α

$$\Delta L = \alpha L_0 \Delta T$$

SI unit for α: $\mathrm{K}^{-1} = (\mathrm{C}^\circ)^{-1}$

Definition of Coefficient of Volume Expansion, β

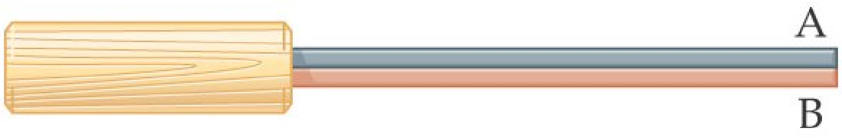
$$\Delta V = \beta V \Delta T$$

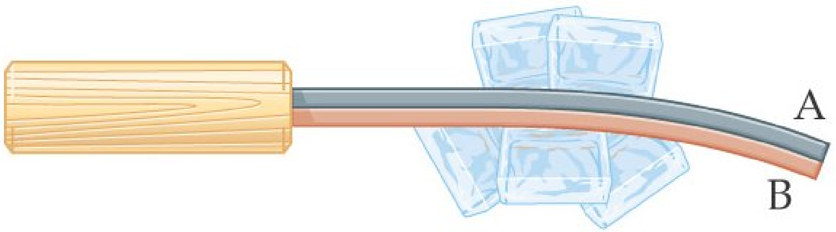
SI unit for β: $\mathrm{K}^{-1} = (\mathrm{C}^\circ)^{-1}$

Substance	**Coefficient of linear expansion, α (K^{-1})**
Lead	29×10^{-6}
Aluminum	24×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Iron (steel)	12×10^{-6}
Concrete	12×10^{-6}
Window glass	11×10^{-6}
Pyrex glass	3.3×10^{-6}
Quartz	0.50×10^{-6}

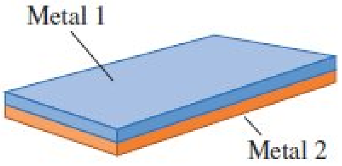
A common type of thermometer uses a *bimetallic strip*

A bimetallic strip consists of two metals of different coefficients of thermal expansion, A and B in the figure. It will bend when heated or cooled.

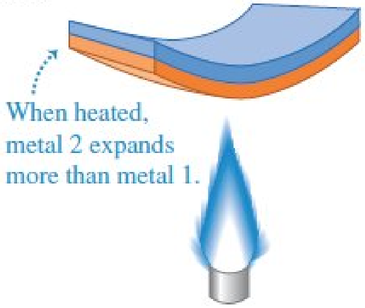




(a) A bimetallic strip

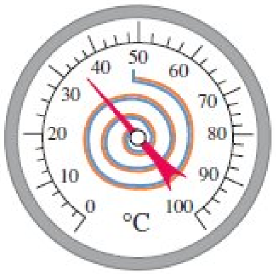


(b) The strip bends when its temperature is raised.



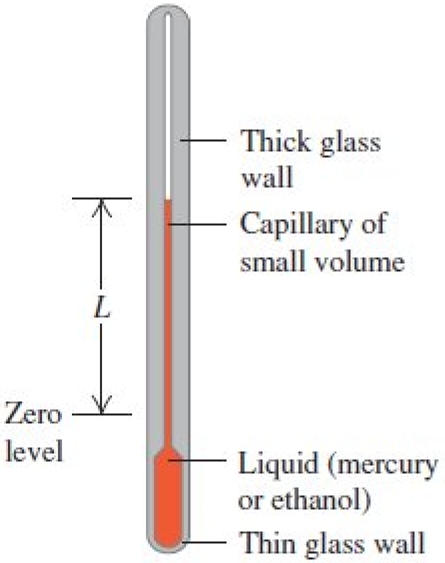
When heated, metal 2 expands more than metal 1.

(c) A bimetallic strip used in a thermometer

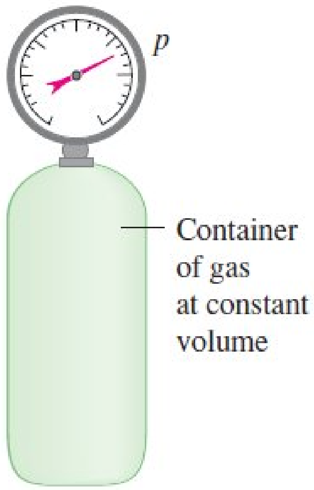


Devices for measuring temperature.

(a) Changes in temperature cause the liquid's volume to change.



(b) Changes in temperature cause the pressure of the gas to change.

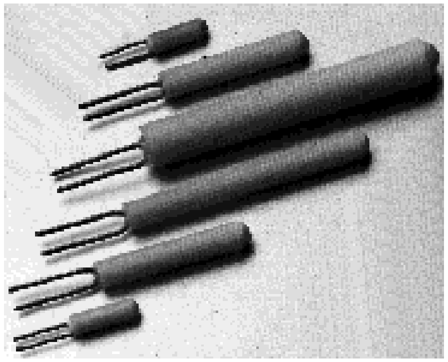


In a *resistance thermometer* the changing electrical resistance of a coil of fine wire, a carbon cylinder, or a germanium crystal is measured. Resistance thermometers are usually more precise than most other types.

$$R = R_0(1 + a\,\theta\,)$$

Metal	Rezistivity at 0 °C	Fussion point	Working range	R100/R0
	μΩ.cm	°C	°C	
Cu	7	1083	-190 à +150	1,427
Ni	6,38	1453	-60 à +180	1,672
Pt	9,81	1769	-250 à +1100	1,392
In	9	153	-269 à +27	

The thermistance



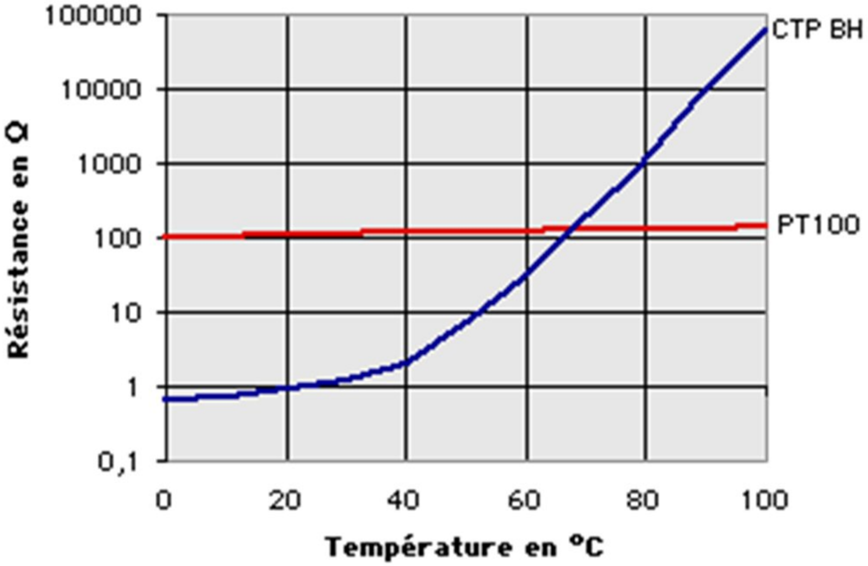
A thermistor is an agglomerate of sintered metal oxides, that is to say compacted by high pressure exerted at high temperature, of the order of 150 bars and 1000 ° C.

Temperature variation law:

$$\boxed{R = ae^{\frac{b}{\theta}}}$$

a and b are two parameters of the thermistance.

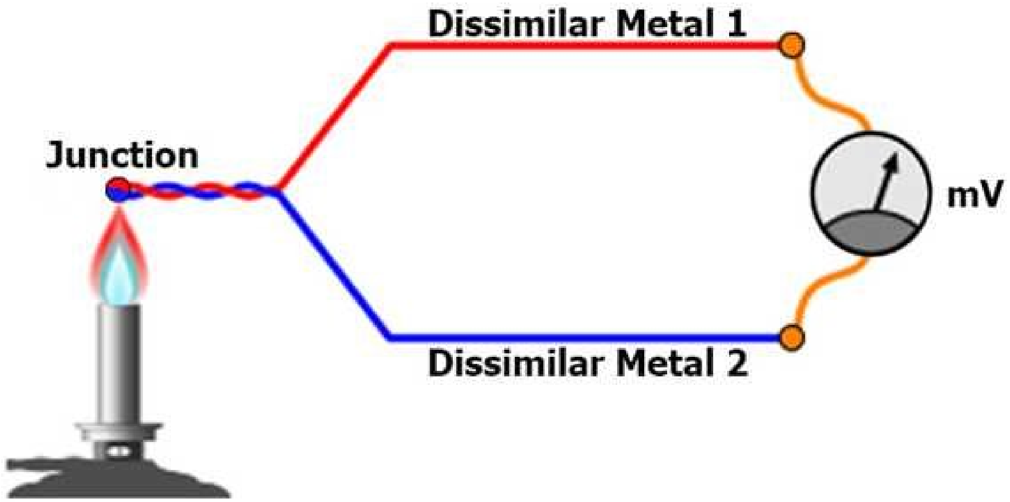
Comparison with a resistance thermometer

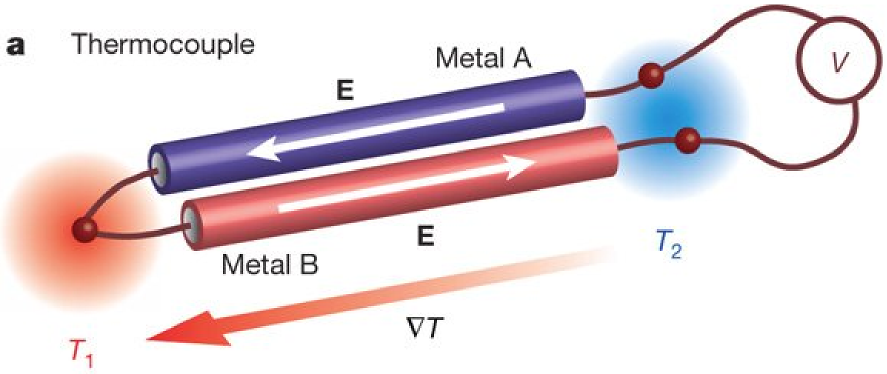


The variation of the resistivity is much greater for a thermistor.
The thermistor is not linear.

Temperature range :	Working range: -80 à +700 C
Precission :	1/10 to ½ of degree
Inconvenient :	The law of variation of resistance as a function of temperature is not linear.

The thermocouple





By heating the junction of the two different metals A and B, a voltage e_{AB} appears (the Seebeck effect);
it depends on the temperature of the junction.

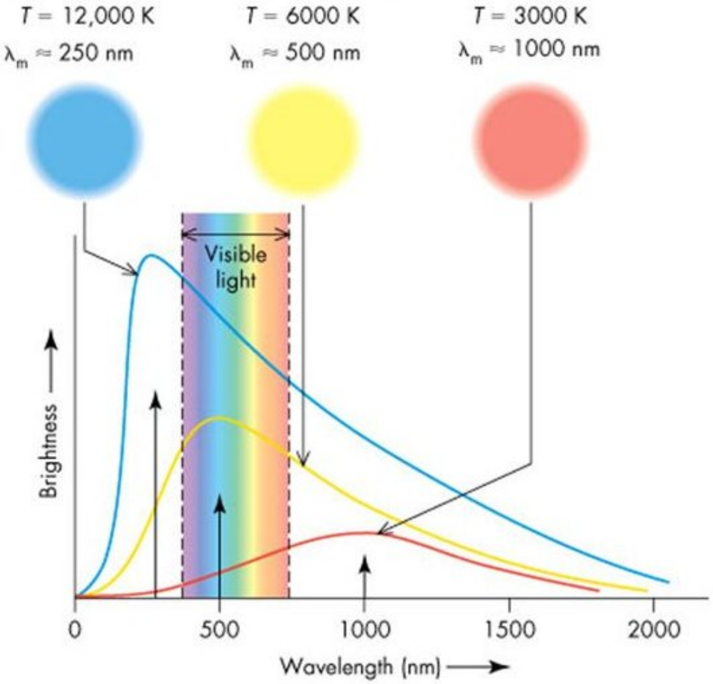
Non-contact measuring of the temperature (radiation)

Some thermometers detect the amount of infrared radiation emitted by an object.

All objects emit electromagnetic radiation, including infrared, as a consequence of their temperature) .

Wien’s law

$$T = \frac{2.9 \times 10^{-3}}{\lambda_{max}}$$



One example is a *temporal artery thermometer.*

an infrared sensor in the thermometer measures the radiation from the skin.

This device gives more accurate values of body temperature than do oral or ear thermometers.

3. Heat and internal energy

Internal energy:

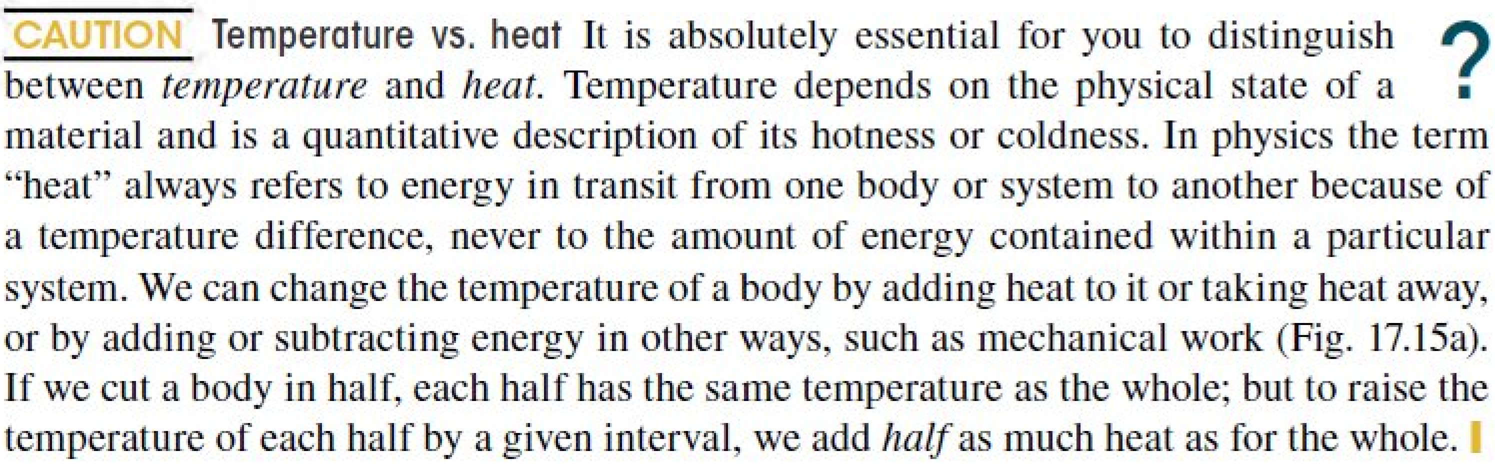
U

represents the total energy of a system associated to its microscopic components (atoms, molecules…) as analysed from a referential in rest with respect to the centre of the mass of the system

Heat:

Q

When you put a cold spoon into a cup of hot coffee, the spoon warms up and the coffee cools down as they approach thermal equilibrium. What causes these temperature changes is a transfer of energy from one substance to another. Energy transfer that takes place solely because of a temperature difference is called heat flow or heat transfer, and energy transferred in this way is called heat.

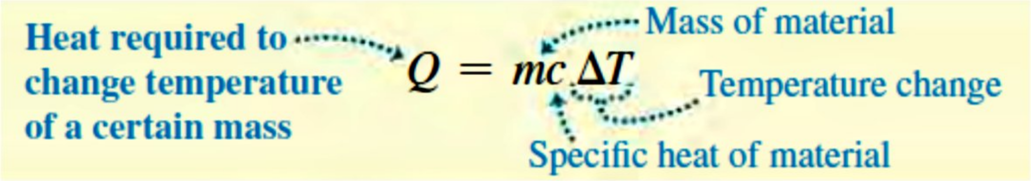


CAUTION **Temperature vs. heat** It is absolutely essential for you to distinguish between *temperature* and *heat*. Temperature depends on the physical state of a material and is a quantitative description of its hotness or coldness. In physics the term "heat" always refers to energy in transit from one body or system to another because of a temperature difference, never to the amount of energy contained within a particular system. We can change the temperature of a body by adding heat to it or taking heat away, or by adding or subtracting energy in other ways, such as mechanical work (Fig. 17.15a). If we cut a body in half, each half has the same temperature as the whole; but to raise the temperature of each half by a given interval, we add *half* as much heat as for the whole.

Specific heat

The quantity of heat Q required to increase the temperature of a mass m of a certain material from T1 to T2

The quantity of heat needed also depends on the nature of the material; raising the temperature of 1 kilogram of water by 1 C requires 4190 J of heat, but only 910 J is needed to raise the temperature of 1 kilogram of Aluminum by 1 C.



$$Q = mc\,\Delta T$$

The calorie (*abbreviated cal*) is defined as the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C.

A corresponding unit of heat using Fahrenheit degrees and British units is the British thermal unit, or Btu. One Btu is the quantity of heat required to raise the temperature of 1 pound (weight) of water $1F^{o}$ from 63 ^{o}F to 64 ^{o}F

$$\begin{aligned} 1\ \text{cal} &= 4.186\ \text{J} \\ 1\ \text{kcal} &= 1000\ \text{cal} = 4186\ \text{J} \\ 1\ \text{Btu} &= 778\ \text{ft}\cdot\text{lb} = 252\ \text{cal} = 1055\ \text{J} \end{aligned}$$

The specific heat of water is approximately

$$4190\ \text{J/kg}\cdot\text{K} \qquad 1\ \text{cal/g}\cdot\text{C}^{\circ} \qquad \text{or} \qquad 1\ \text{Btu/lb}\cdot\text{F}^{\circ}$$

Ex. Overheating electronics

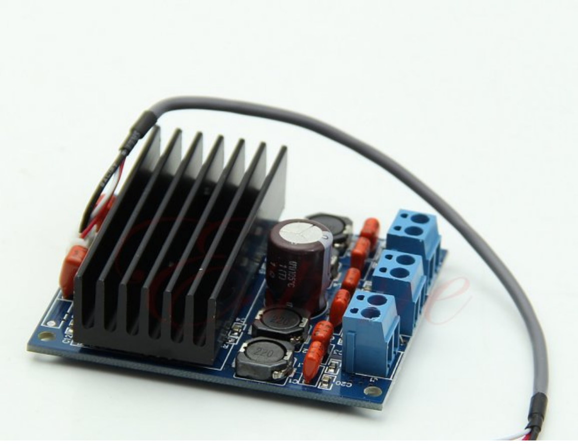
*You are designing an electronic circuit element made of 23 mg of silicon. The electric current through it adds energy at the rate of 7.4 mW = 7.4 * 10^{-3} J/s. If your design doesn't allow any heat transfer out of the element, at what rate does its temperature increase? The specific heat of silicon is 705 J/kg .K.*

$$Q = mc\Delta T \quad \Rightarrow \quad \frac{dQ}{dt} = mc\frac{\Delta T}{dt}$$

$$\Rightarrow \quad \frac{\Delta T}{dt} = \frac{1}{mc}\frac{dQ}{dt} = 7.4\cdot10^{-3}\frac{1}{23\cdot10^{-3}\cdot705} = 0.46\mathrm{K/s}$$

At this rate of temperature rise (27 K min), the circuit element would soon self-destruct. Heat transfer is an important design consideration in electronic circuit elements.

Cooling by radiation and/or convection



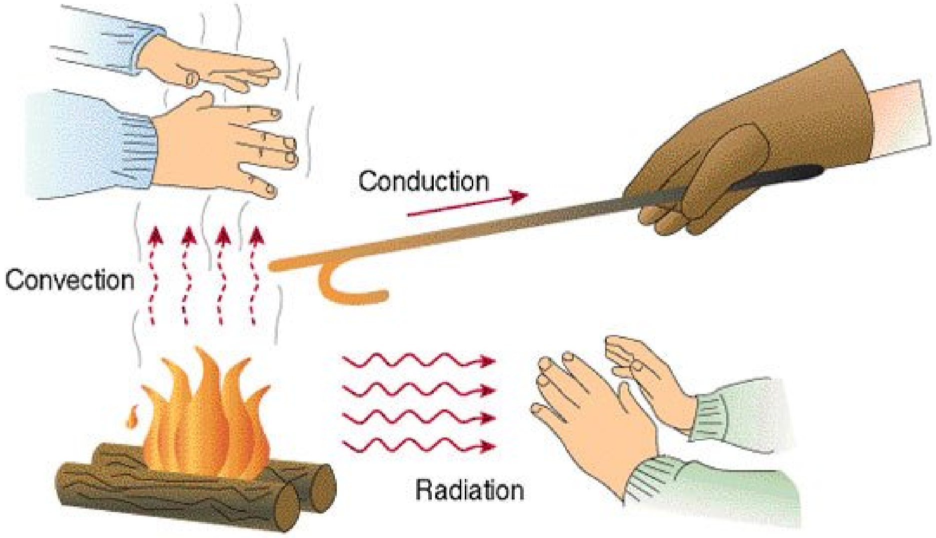
Water cooling of processor

4. Mechanisms of Heat Transfer

There are materials that *permit* or *prevent* heat transfer between bodies.
These are (thermal) *conductors* and *insulators*, respectively.

The three main mechanisms of heat transfer are *conduction*, *convection*, and *radiation*.

- ☐ Conduction occurs within a body or between two bodies in contact.
- ☐ Convection depends on motion of mass from one region of space to another.
- ☐ Radiation is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between bodies.



...Now let's look in more detail at *rates* of energy transfer.

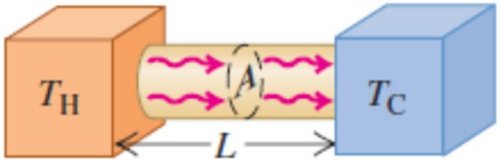
(1) Conduction

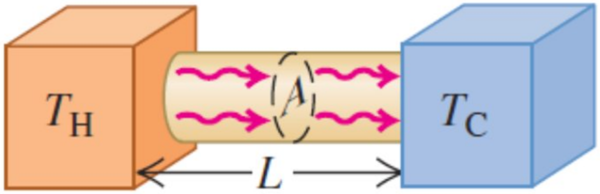
If you hold one end of a copper rod and place the other end in a flame, the end you are holding gets hotter and hotter, even though it is not in direct contact with the flame. Heat reaches the cooler end by conduction through the material.

On the atomic level: *the atoms in the hotter regions have more kinetic energy, on the average, than their cooler neighbours. They knock their neighbours, giving them some of their energy. The neighbours knock their neighbours, and so on through the material. The atoms themselves do not move from one region of material to another, but their energy does.*

In metals another, more effective mechanism is involved to conduct heat. Within the metal, some electrons can leave their parent atoms and wander through the crystal lattice. These *"free" electrons* can rapidly carry energy from the hotter to the cooler regions of the metal, so metals are generally good conductors of heat. A metal rod at 20C feels colder than a piece of wood at 20C because heat can flow more easily from your hand into the metal. The presence of "free" electrons also causes most metals to be good electrical conductors.

- ❑ Heat transfer occurs only between regions that are at different temperatures.
- ❑ The direction of heat flow is always from higher to lower temperature.





A = section, L –length of conductor

The heat current: $H = \frac{dQ}{dt}$ = Rate of heat flow

$H \sim A$
$H \sim (T_H - T_C)$
$H \sim 1/L$

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \quad \text{(heat current in conduction)}$$

k = the thermal conductivity of the material

$(T_H - T_C)/L$ = the temperature difference per unit length = magnitude of the thermal gradient

Generalization:

$$H = \frac{dQ}{dt} = -kA\frac{dT}{dx}$$

The negative sign shows that heat always flows in the direction of decreasing temperature.

$$\frac{H}{A} = j_Q = -k\frac{dT}{dx}$$

j_Q= density of heat current

If the temperature varies along x ,y, z

$$\nabla T = grad\left(T\right) = \frac{\partial T}{\partial x}\vec{i} + \frac{\partial T}{\partial y}\vec{j} + \frac{\partial T}{\partial z}\vec{k}$$

➡ $$\boxed{\vec{j}_Q = -k\nabla T}$$

Fourier law for thermal conduction

Equivalence with the Ohm’s law in electricity (2nd term)

$$\boxed{\vec{j} = \sigma\vec{E} = -\sigma\nabla V}$$

Electric charge current density

$$j = \frac{1}{A}\frac{dq}{dt} = \frac{I}{A}$$

σ =Electric conductivity

ρ =1/σ = electric resistivity

Thermal Conductivities

Substance	***k*** **(W/m·K)**
Metals	
Aluminum	205.0
Brass	109.0
Copper	385.0
Lead	34.7
Mercury	8.3
Silver	406.0
Steel	50.2

Solids (representative values)	
Brick, insulating	0.15
Brick, red	0.6
Concrete	0.8
Cork	0.04
Felt	0.04
Fiberglass	0.04
Glass	0.8
Ice	1.6
Rock wool	0.04
Styrofoam	0.027
Wood	0.12–0.04

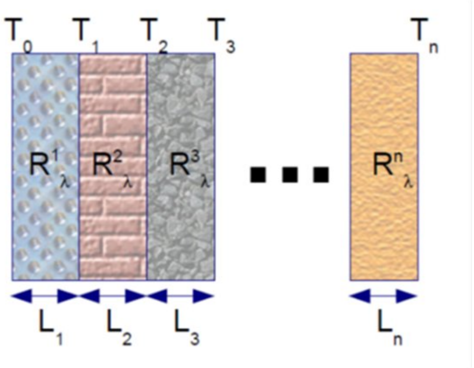
Gases	
Air	0.024
Argon	0.016
Helium	0.14
Hydrogen	0.14
Oxygen	0.023

For thermal insulation in buildings, engineers use the concept of thermal resistance, denoted by R.

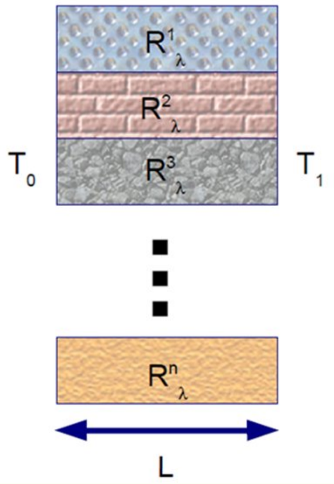
$$R = \frac{L}{k}$$

[R] = 1 m^2 K/W.

Serial (stratified materials)



parallel



$$R_\lambda^{série} = R_\lambda^1 + R_\lambda^2 + R_\lambda^3 + \cdots + R_\lambda^n$$

$$\frac{1}{R_{\text{parallèle}}} = \frac{1}{R_\lambda^1} + \frac{1}{R_\lambda^2} + \frac{1}{R_\lambda^3} + \cdots + \frac{1}{R_\lambda^n}$$

L = 20 cm brick $R_c = 1{,}33 \frac{m^2 K}{W}$

L = 20 cm polysthrene $R_c = 4 \frac{m^2 K}{W}$

L = 20 cm concrete $R_c = 0{,}21 \frac{m^2 K}{W}$

Ob: 10 cm polysthren <=> 1,6m concrete !

→ $R_{min} = 1{,}4 \frac{m^2 K}{W}$ (indicative C107/2005)

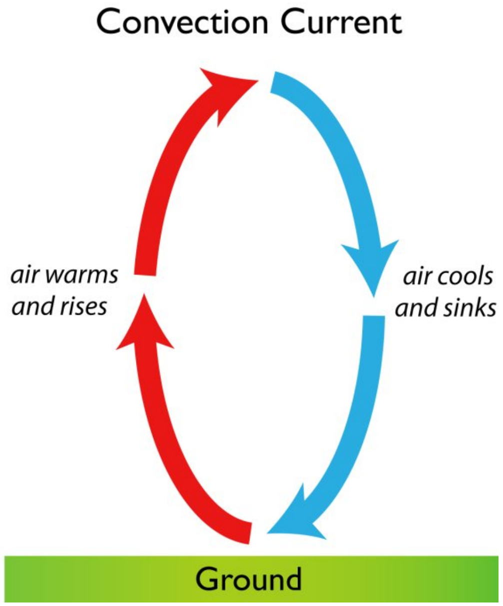
minimum thermal rezistance required for house isolation

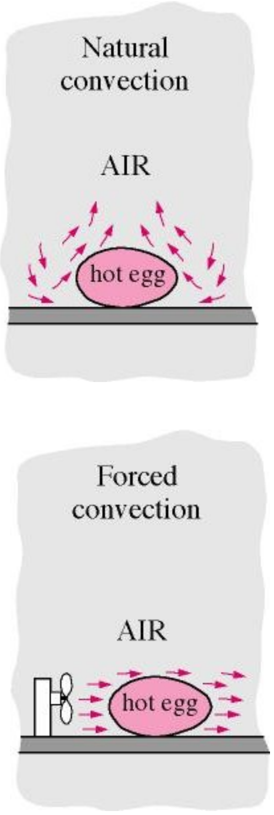
(2) Convection

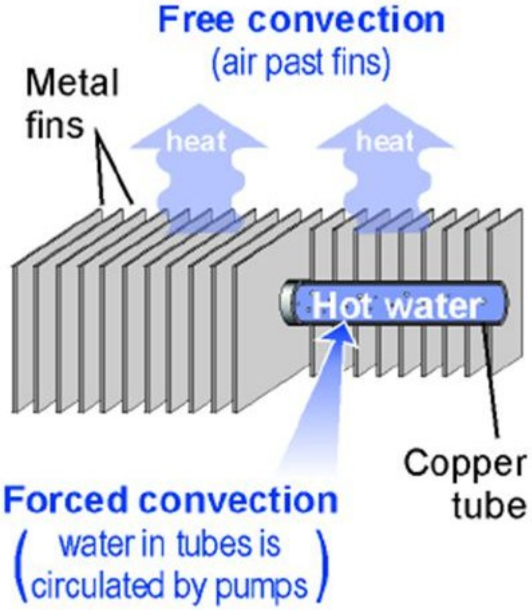
Convection is the transfer of heat by mass motion of a fluid from one region of space to another.

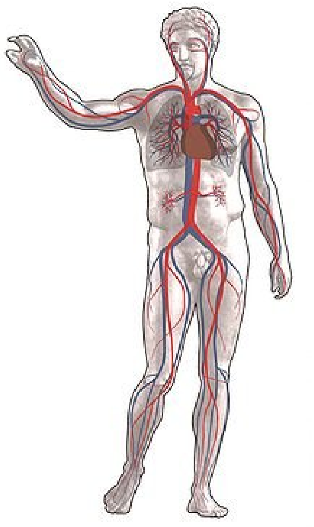
Ex. *hot-air and hot-water home heating systems, the cooling system of an automobile engine, and the flow of blood in the body.*

- ☐ If the fluid is circulated by a blower or pump, the process is called forced convection;
- ☐ if the flow is caused by differences in density due to thermal expansion, such as hot air rising, the process is called natural convection or free convection









The most important mechanism for heat transfer within the human body (needed to maintain nearly constant temperature in various environments) is forced convection of blood, with the heart serving as the pump.

Convective heat transfer is a very complex process, and there is no simple equation to describe it. Here are a few experimental facts:

1. *The heat current due to convection is directly proportional to the surface area. This is the reason for the large surface areas of radiators and cooling fins*.

2. The viscosity of fluids slows natural convection near a stationary surface, giving a surface film that on a vertical surface typically has about the same insulating value as 1.3 cm of plywood (R=0.7). Forced convection decreases the thickness of this film, increasing the rate of heat transfer. This is the reason for the "wind-chill factor"; you get cold faster in a cold wind than in still air with the same temperature.

3. The heat current due to convection is found to be approximately proportional to the 5/4 power of the temperature difference between the surface and the main body of fluid.

Newton's law

$$\dot{Q} = \alpha A (T_s - T_\infty)$$

α : convective exchange coefficient (W m^{-2} K^{-1})
T_s : the temperature of the considered surface
T_∞: the fluid temperature far away from the surface

(3) Radiation

Radiation is the transfer of heat by electromagnetic waves such as visible light, infrared, and ultraviolet radiation.

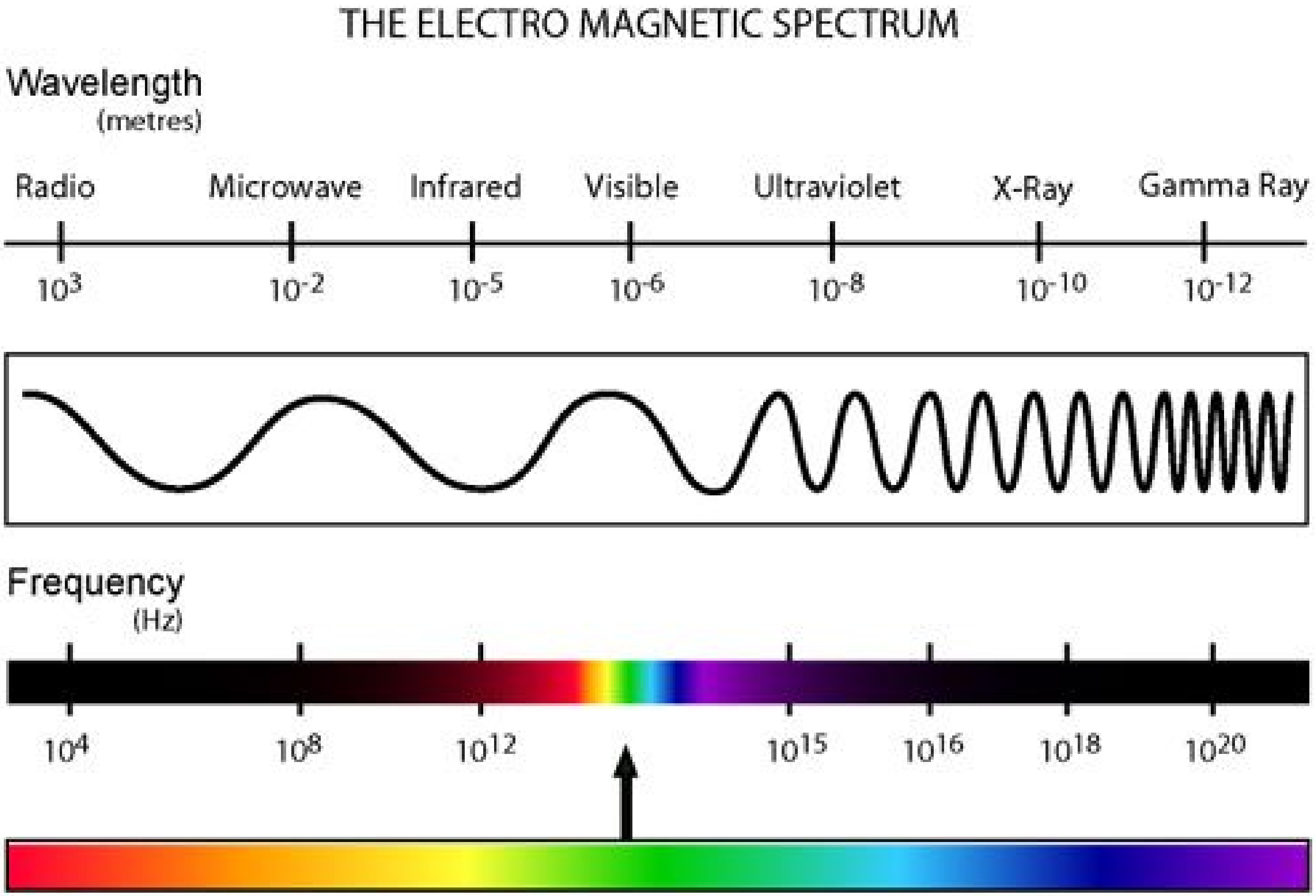
Every body, even at ordinary temperatures, emits energy in the form of electromagnetic radiation.

$$\boxed{I_Q = \frac{dQ}{dt} = Ae\sigma T^4}$$

Stefan – Boltzmann law

σ = 5.6704001402 * 10^{-8} W/m^2 K^4
Stefan Boltzmann constant
A = area of emitting surface
e = emissivity (0<e<1)
I_Q = heat current (dQ/dt)

- ☐ Around 20C nearly all the energy is carried by infrared waves with wavelengths much longer than those of visible light. As the temperature rises, the wavelengths shift to shorter values.
- ☐ At 800C, a body emits enough visible radiation to appear “red-hot,” although even at this temperature most of the energy is carried by infrared waves.
- ☐ At 3000K the temperature of an incandescent lamp filament, the radiation contains enough visible light that the body appears “white-hot.”



see next term

Radiation and Absorption

While a body at absolute temperature T is radiating, its surroundings at temperature T_S are also radiating, and the body absorbs some of this radiation. If it is in thermal equilibrium with its surroundings $T=T_S$, and the rates of radiation and absorption must be equal.

The *net* rate of out of radiation from a body at temperature *T* with surroundings at temperature T_S is:

$$H_{\text{net}} = Ae\sigma T^4 - Ae\sigma T_s^{\,4} = Ae\sigma(T^4 - T_s^{\,4})$$

=> for radiation, as for conduction and convection, the heat current depends on the temperature difference between two bodies.

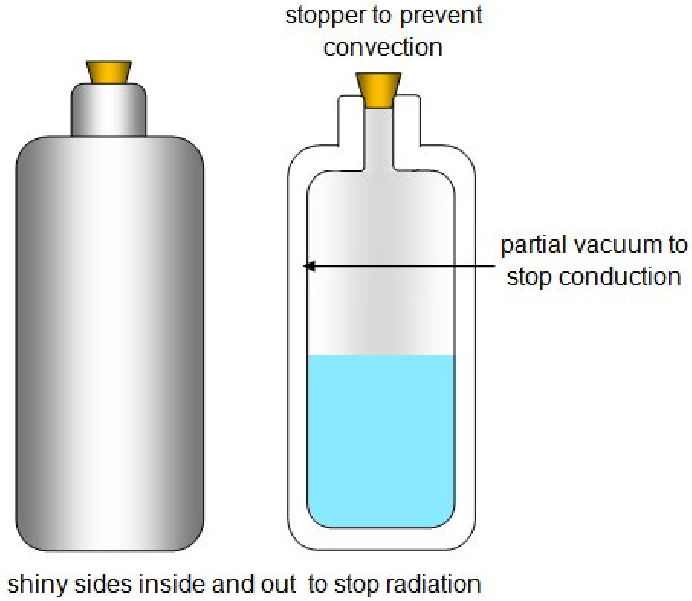
Applications of Radiation

A body that is a good absorber must also be a good emitter.

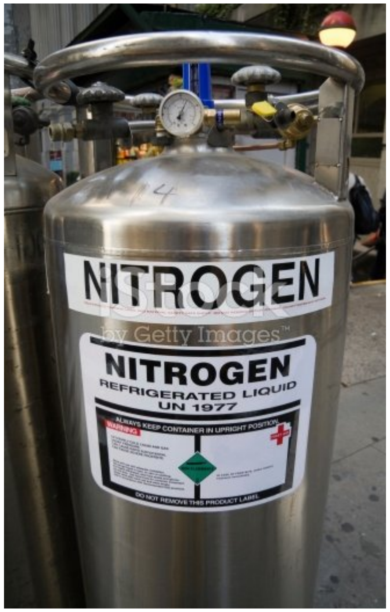
An ideal radiator, with an *emissivity of unity*, is also an ideal absorber, absorbing all of the radiation that strikes it. Such an ideal surface is called an ideal black body or simply a blackbody.

Conversely, an ideal reflector, which absorbs no radiation at all, is also a very ineffective radiator.

This is the reason for the silver coatings on vacuum (“Thermos”) bottles, invented by Sir James Dewar (1842–1923).



- ✓ Vacuum bottle has double glass walls.
- ✓ The air is pumped out of the spaces between the walls; this eliminates nearly all heat transfer by conduction and convection.
- ✓ The silver coating on the walls reflects most of the radiation from the contents back into the container, and the wall itself is a very poor emitter.
- ✓ Thus a vacuum bottle can keep coffee, tea, soup… hot for several hours.

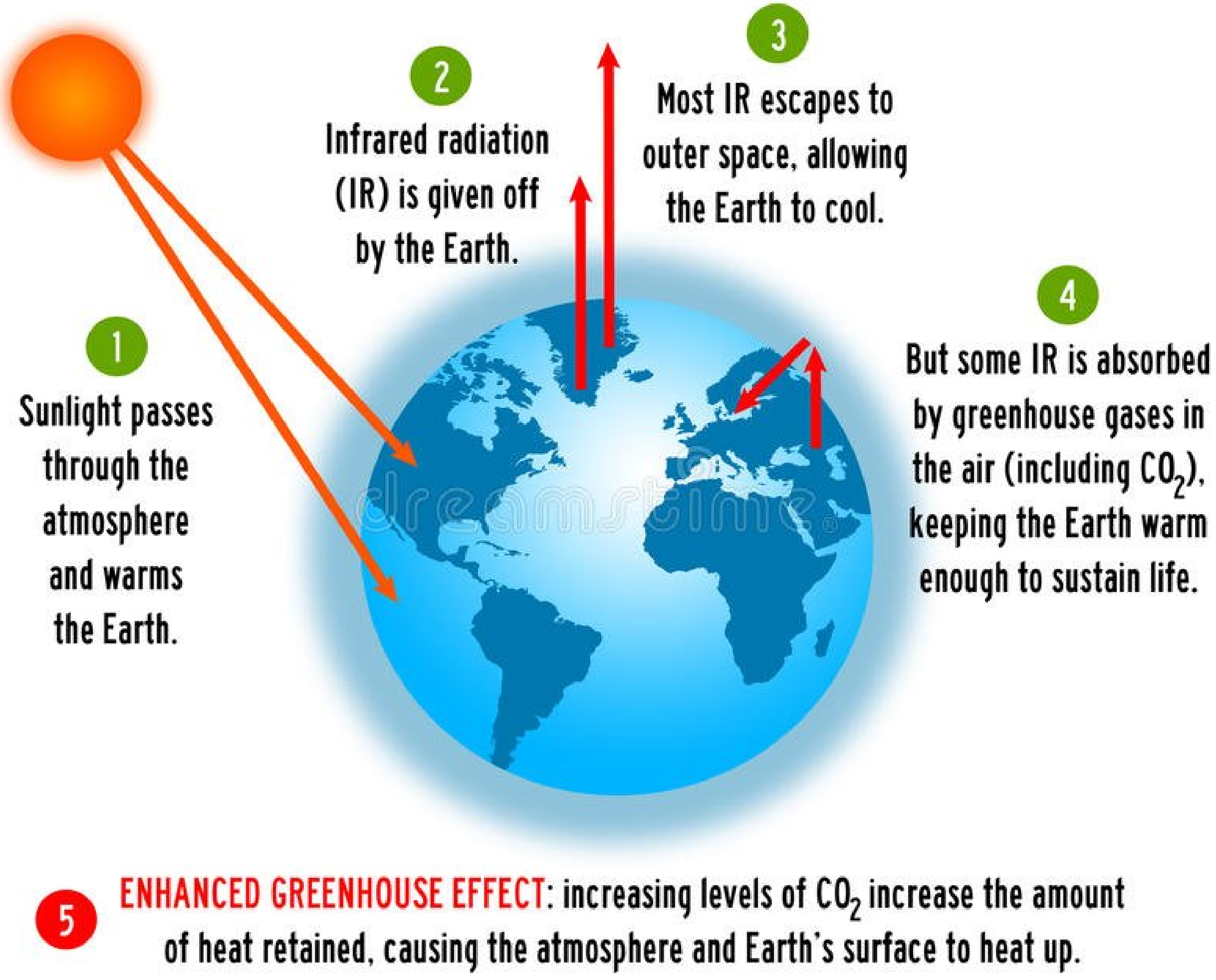


The Dewar flask, used to store very cold liquefied gases, is exactly the same in principle.

- Liquid N_2 (T=70K =-203.16^{o}C)
- For Liquid He (T=4.2K=-268.96^{o}C) one uses a double Dewar system with intermediate space filled with liquid N2.

Radiation, Climate, and Climate Change

Our planet constantly absorbs radiation coming from the sun.
In thermal equilibrium, the rate at which our planet absorbs solar radiation must equal the rate at which it emits radiation into space.
The presence of an atmosphere on our planet has a significant effect on this equilibrium.



1 Sunlight passes through the atmosphere and warms the Earth.

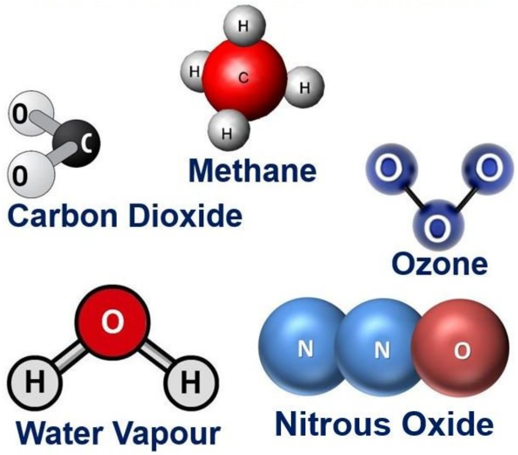
2 Infrared radiation (IR) is given off by the Earth.

3 Most IR escapes to outer space, allowing the Earth to cool.

4 But some IR is absorbed by greenhouse gases in the air (including CO_2), keeping the Earth warm enough to sustain life.

5 **ENHANCED GREENHOUSE EFFECT**: increasing levels of CO_2 increase the amount of heat retained, causing the atmosphere and Earth's surface to heat up.

greenhouse gases

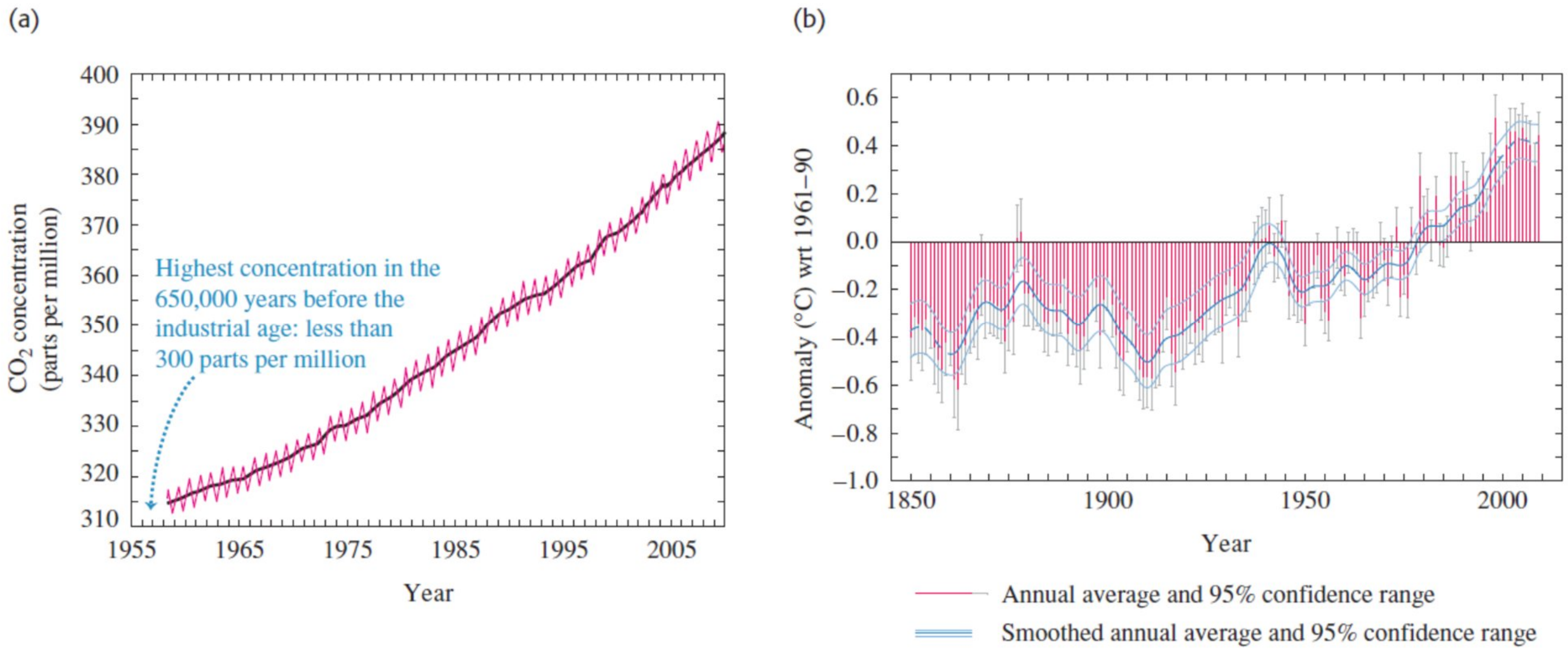


Benefit:

Without the greenhouse effect the average temperature on the Earth would be -18C instead of +15C !!!

However…

- *However*, the burning of fossil fuels such as coal and petroleum has elevated the atmospheric concentration of CO_2 to unprecedented levels.
- As a consequence, since the 1950s the global average surface temperature has increased by 0.6^{o}C and the earth has experienced the hottest years ever recorded.



(a) The concentration of atmospheric CO_2 has increased by 22% since continuous measurements began in 1958. (The yearly variations are due to increased intake of by plants in spring and summer.) (b) The increase in global average temperature since the beginning of the industrial era is a result of the increase in CO_2 concentration.

5. Principles (laws) of Thermodynamics

I) The first Law of Thermodynamics

The first law of thermodynamics, also known as Law of Conservation of Energy, states that *energy can neither be created nor destroyed; energy can only be transferred or changed from one form to another*.

When heat is added into a system it can either:

(1) change the internal energy of the system (i.e. make it hotter) or

(2) go into doing work.

$$Q=W+\Delta U$$

- This law says that there are two kinds of processes, heat and work, that can lead to a change in the internal energy of a system. Since both heat and work can be measured and quantified, this is the same as saying that any change in the energy of a system must result in a corresponding change in the energy of the surroundings outside the system. In other words, energy cannot be created or destroyed.

- If heat flows into a system or the surroundings do work on it, the internal energy increases and the sign of Q and W are positive.

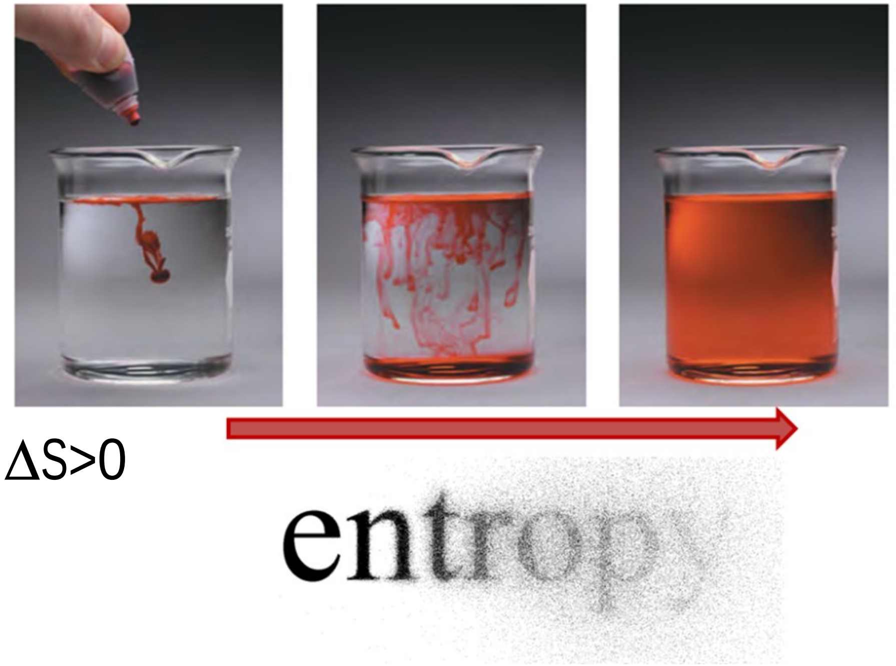
- Conversely, heat flow out of the system or work done by the system (on the surroundings) will be at the expense of the internal energy, and Q and W will therefore be negative.

II) The Second Law of Thermodynamics

The first principle of thermodynamics is an affirmation of the equivalence of the various forms of energy and the conservation of it.

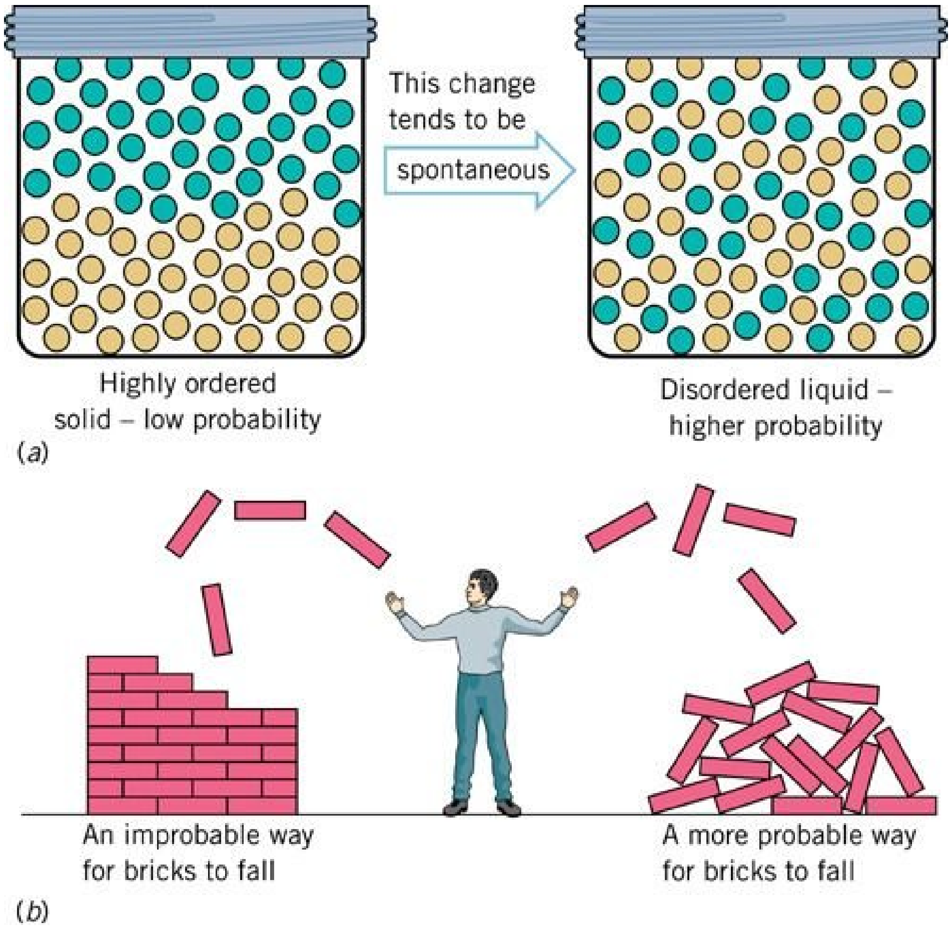
Although the first law of thermodynamics provides an energy balance, it *does not provide any indication of why a process is taking place in a given direction*.

The second law of thermodynamics
introduces the notion of entropy (S), a measure of system disorder.



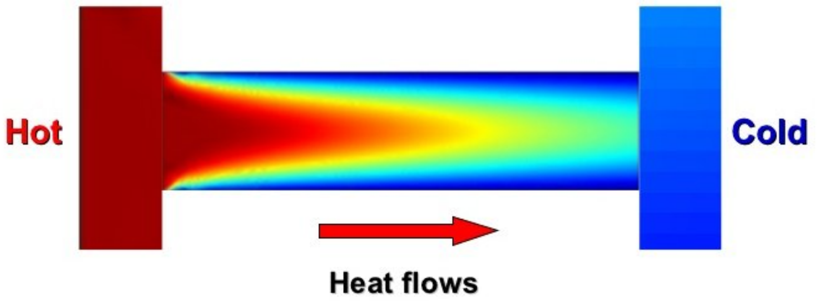
If a reversible process occurs, there is no net change in entropy. In an irreversible process, entropy always increases, so the change in entropy is positive. The total entropy of the universe is continually increasing.

The level of disorder in the universe is steadily increasing. Systems tend to move from ordered behaviour to more random behaviour.


This change tends to be
spontaneous
Highly ordered solid – low probability
Disordered liquid – higher probability
(a)
An improbable way for bricks to fall
A more probable way for bricks to fall
(b)

The 2nd Law can also be stated that heat flows spontaneously from a hot object to a cold object *(spontaneously means without the assistance of external work).*

- **Heat** will flow between two bodies as long as there is **temperature difference** between them.

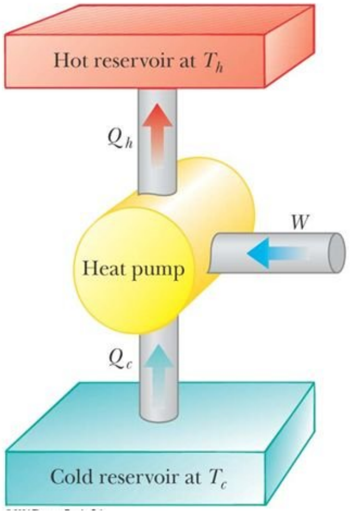


When opening the window in winter,

- ☐ the heat is going out,
- ☐ the cold is NOT entering!

Non-spontaneous heat-pump process allows extracting heat from cold and exhausted to the hot reservoir.

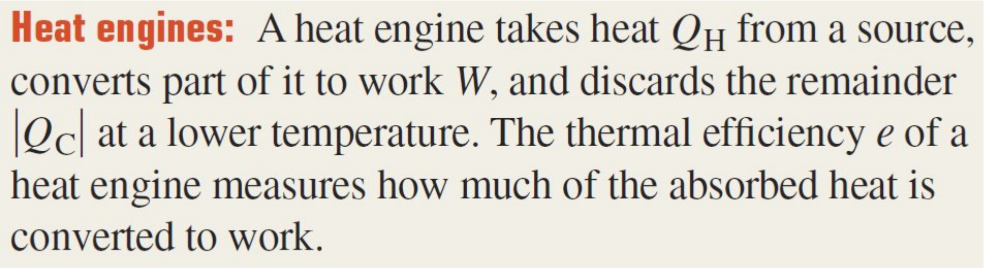
- Energy is extracted from the cold reservoir, Q_C
- Energy is transferred to the hot reservoir, Q_h
- Work must be done *on* the engine, W



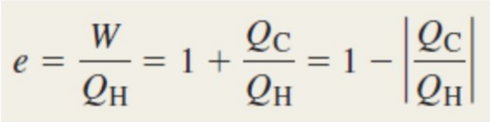
Refrigerators, air conditioners, heat pumps

The second principle of thermodynamics is used to determine the theoretical limits for the performance of mostly used engineering systems like heat engines, heat pumps, refrigerators,…

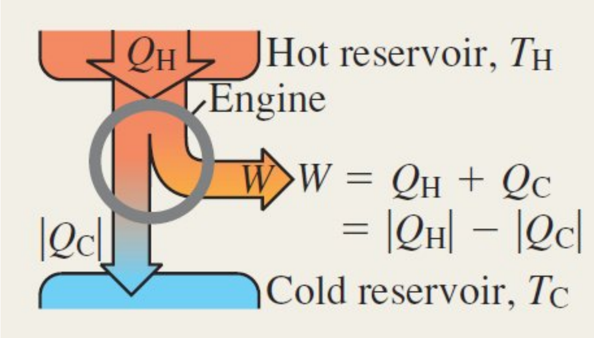
- ☐ *The engine statement* is that no cyclic process can convert heat completely into work.
- ☐ *The refrigerator statement* is that no cyclic process can transfer heat from a colder place to a hotter place with no input of mechanical work.

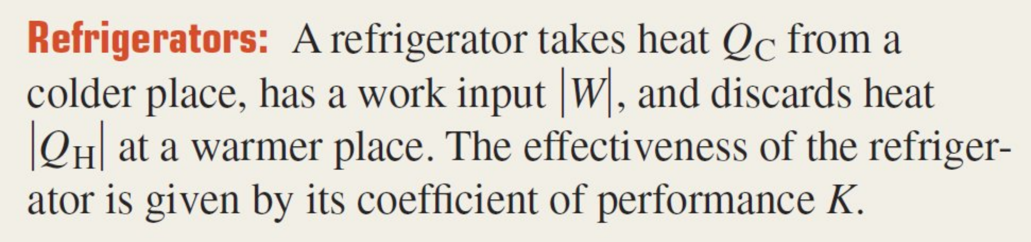


Heat engines: A heat engine takes heat Q_H from a source, converts part of it to work W, and discards the remainder $|Q_C|$ at a lower temperature. The thermal efficiency e of a heat engine measures how much of the absorbed heat is converted to work.

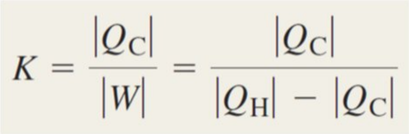


$$e = \frac{W}{Q_H} = 1 + \frac{Q_C}{Q_H} = 1 - \left|\frac{Q_C}{Q_H}\right|$$

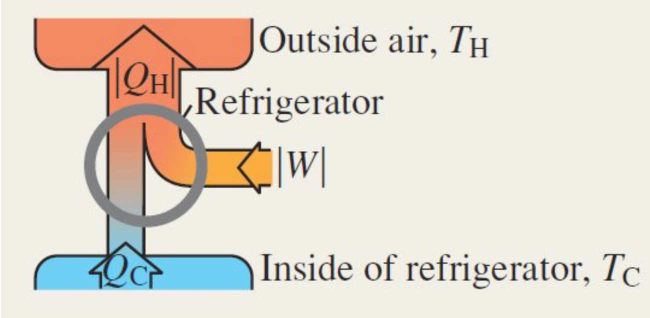




Refrigerators: A refrigerator takes heat Q_C from a colder place, has a work input $|W|$, and discards heat $|Q_H|$ at a warmer place. The effectiveness of the refrigerator is given by its coefficient of performance K.



$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$



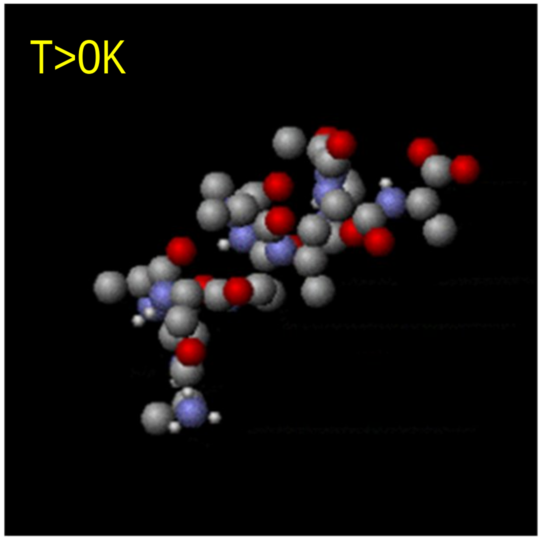
III) The third Law of Thermodynamics

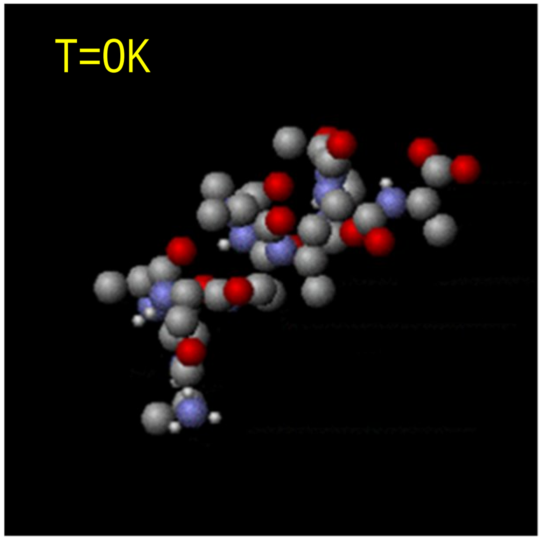
also called Nernst's theorem, named after the Nobel Prize winner who enounced it in 1906, is stated as follows (different formulations):

(1) Planck: "*the entropy of any system tends to an absolute constant which can be considered zero when the temperature tends to absolute zero*."

or (2) "*At the temperature of zero Kelvin, the entropy of any pure body, perfectly crystallized in its stable form, is zero*."

Atoms vibrate around their equilibrium position





Atoms get locked in their equilibrium position

(3) "It is impossible to reduce the temperature of any system to absolute zero in a finite number of operations.“: *absolute zero is a limit temperature impossible to reach*.

The third principle of thermodynamics is associated with the descent of a system in its fundamental quantum state when its temperature approaches a limit that defines the notion of absolute zero.

The third principle is not necessary in classical thermodynamics.

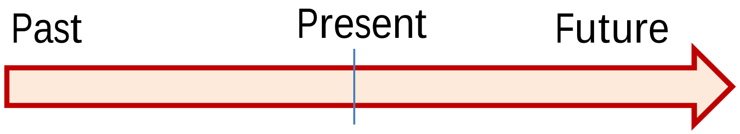
Entropy and time arrow

The arrow of time expresses the fact that in the world about us the past is distinctly different from the future. Milk spills but doesn't unspill; eggs splatter but do not unsplatter; waves break but do not unbreak; we always grow older, never younger. These processes all move in one direction in time - they are called "*time-irreversible*" and define the arrow of time.

- However, nearly all fundamental laws of Physics are symmetric in time.
- Physical processes at the microscopic level are either entirely or mostly time-symmetric: if the direction of time were to reverse, the theoretical statements that describe them would remain true.
- Yet at the macroscopic level it often appears that this is not the case: there is an obvious direction (or flow) of time. This seems correlated to statistical effects (Boltzmann), in a system constituted by an above threshold number of particles (entities) ? *Which is that limit*?.

All phenomena that behave differently in one time direction can ultimately be linked to the Second Law of Thermodynamics.

The arrow of time in various phenomena

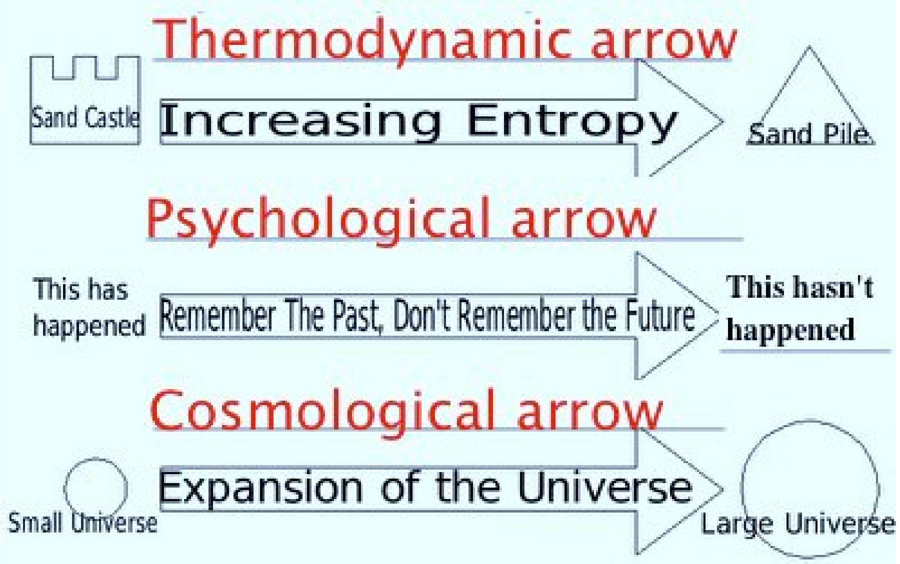


Past

Present

Future

The thermodynamic arrow of time
The thermodynamic arrow of time is provided by the Second Law of Thermodynamics, which says that in an isolated system, entropy tends to increase with time.



The psychological/perceptual arrow of time
A related mental arrow arises because one has the sense that one's perception is a continuous movement from the known (past) to the unknown (future).

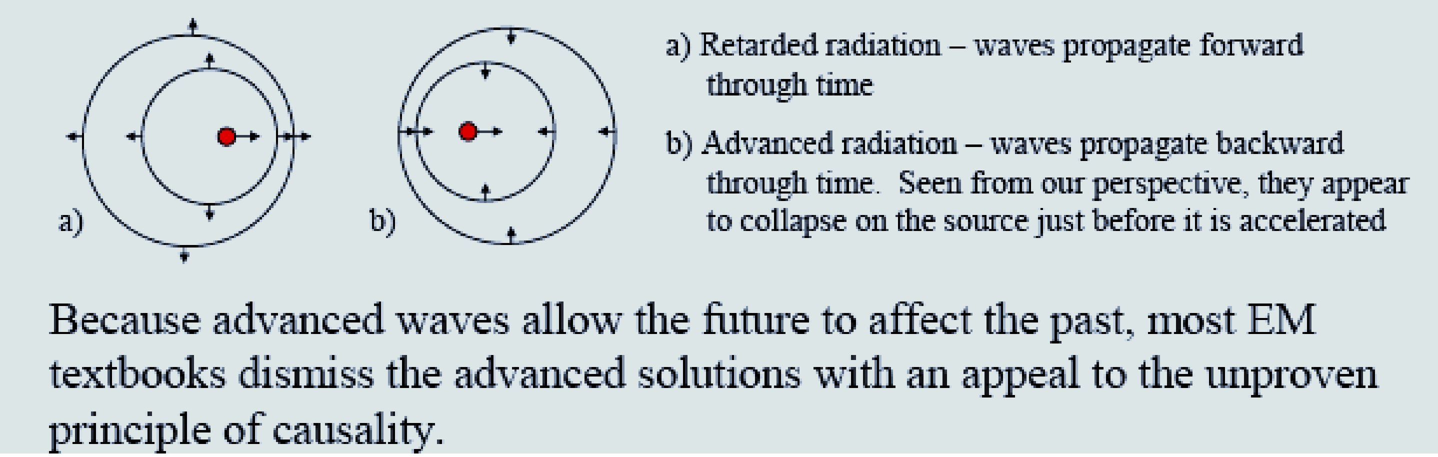
The cosmological arrow of time
The cosmological arrow of time points in the direction of the universe's expansion.

The causal arrow of time
A cause precedes its effect: the causal event occurs before the event it affects. Birth, for example, follows a successful conception and not vice versa. Thus causality is intimately bound up with time's arrow.

The radiative arrow of time

Waves, from radio waves to sound waves to those on a pond from throwing a stone, expand outward from their source, even though the wave equations allow for solutions of convergent waves as well as radiative ones.

This arrow probably follows from the thermodynamic arrow in that meeting the conditions to produce a convergent wave requires more order than the conditions for a radiative wave.



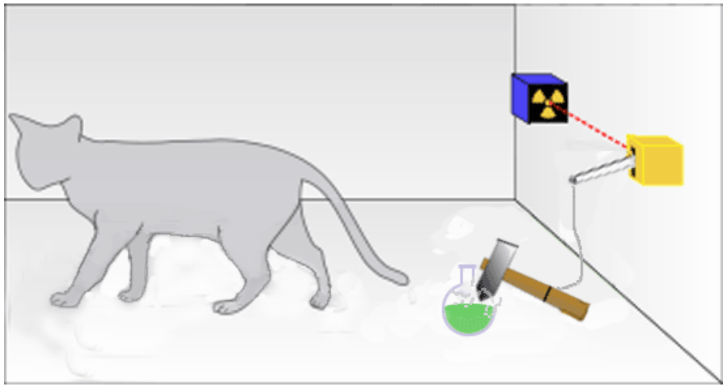
a) Retarded radiation – waves propagate forward through time

b) Advanced radiation – waves propagate backward through time. Seen from our perspective, they appear to collapse on the source just before it is accelerated

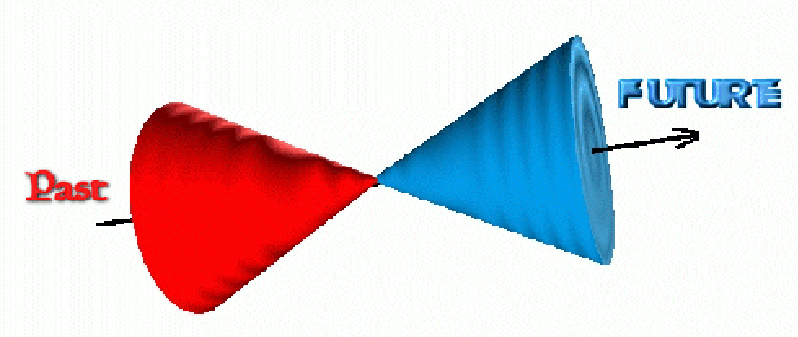
Because advanced waves allow the future to affect the past, most EM textbooks dismiss the advanced solutions with an appeal to the unproven principle of causality.

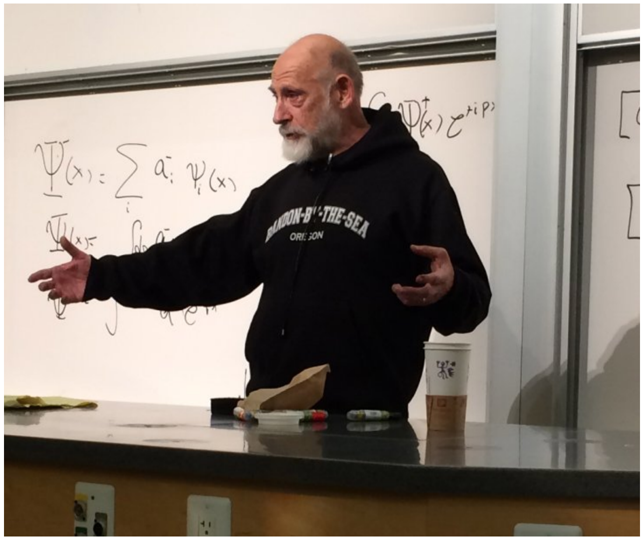
The quantum arrow of time

According to the Copenhagen interpretation of quantum mechanics, quantum evolution is governed by the Schrödinger equation, which is time-symmetric, and by wave function collapse, which is time irreversible.



No going back. Prior to observation, Schrödinger's cat is both alive and dead. Opening the box seals its fate.





Why is Time a One-Way Street?

Leonard Susskind

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

Anyone can see that the past is different from the future. Anyone, that is, but theoretical physicists, whose equations do not seem to distinguish the past from the future. How, then, do physicists understand the "arrow of time" — the fact that the past and future are so different? Leonard Susskind will discuss the paradox of time's arrow and how physicists and cosmologists view it today.

Leonard Susskind is Felix Bloch Professor of Theoretical Physics at Stanford University and Director of the Stanford Institute for Theoretical Physics