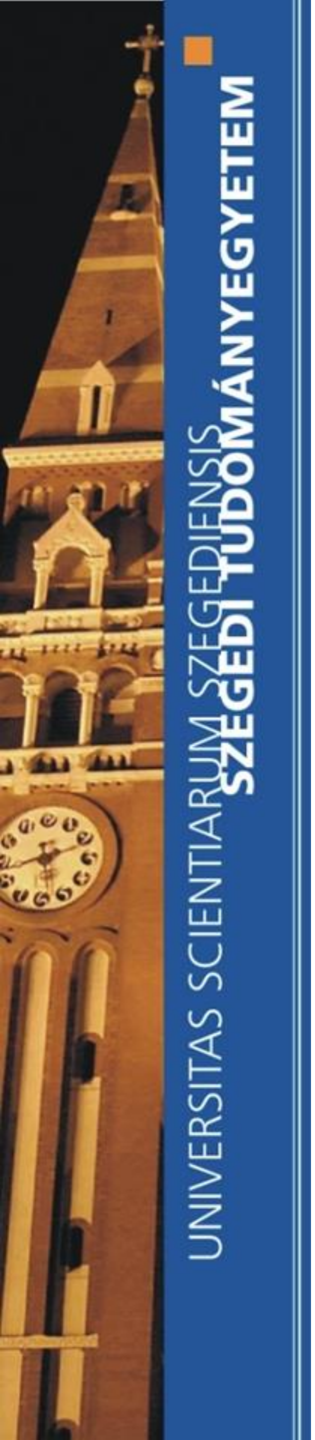


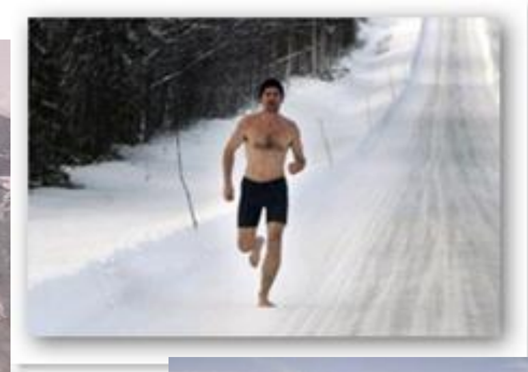
Medical Physics 10.

Thermal interaction between the human body and its environment. Temperature, its measurement, heat, heat transport.

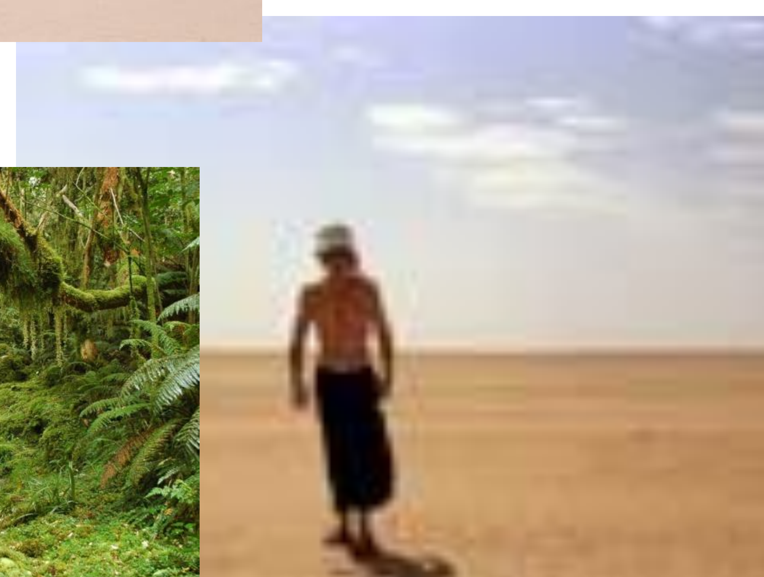
Ferenc Bari

Professor & chairman

Szeged, November 9, 2017.



What is temperature?

An indication of the internal energy contained in a substance

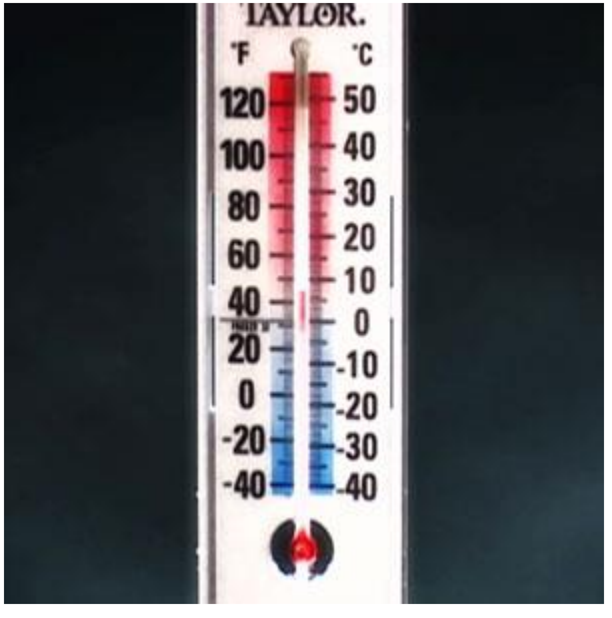
Temperature is a measure of but not directly proportional to internal kinetic energy

The detailed explanation can be found in kinetic theory of gases

For an ideal monatomic gas, the microscopic motions are the translational motions of the constituent gas particles. For a multiatomic gas, vibrational and rotational motion should be included too.

- Temperature is measured with thermometers that may be calibrated to a variety of temperature scales.
- In most of the world (except for the United States, and a few other countries), the degree Celsius scale is used for most temperature measuring purposes.
- The entire scientific world (the U.S. included) measures temperature using the Celsius scale and thermodynamic temperature using the kelvin scale, which is just the Celsius scale shifted downwards so that 0 K = −273.15 °C, or absolute zero.
- The United States is the last major country in which the degree Fahrenheit temperature scale is used by most lay people, medicine,industry, popular meteorology, and government.

•Intuitively, temperature is a measure of how hot or cold something is, although the most immediate way in which we can measure this, by feeling it, is unreliable, resulting in the phenomenon of felt air temperature, which can differ at varying degrees from actual temperature. On the molecular level, temperature is the result of the motion of particles which make up a substance. Temperature increases as the energy of this motion increases.



Comparison of temperature scales

- **Relative Scales**
  - **Fahrenheit (°F)**
  - **Celsius (°C)**
- **Absolute Scale**
  - **Kelvin (K)**

Celsius temperature conversion formulae

	from Celsius	to Celsius
Fahrenheit	$[°F] = [°C] \times \frac{9}{5} + 32$	$[°C] = ([°F] - 32) \times \frac{5}{9}$
Kelvin	$[K] = [°C] + 273.15$	$[°C] = [K] - 273.15$

For temperature *intervals* rather than specific temperatures,
1 °C = 1 K
and
1 ℃ = 1.8 °F

Celsius Scale

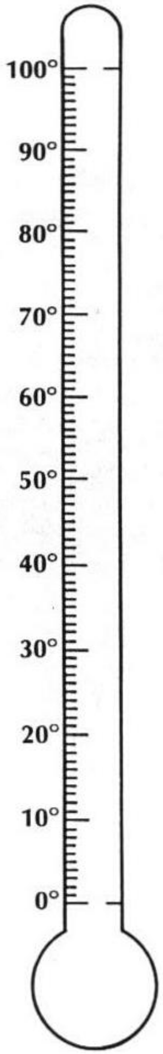
•The **Celsius** temperature scale was previously the **centigrade scale**. The **degree Celsius** (symbol: **℃**) can refer to a specific temperature on the **Celsius scale** as well as serve as a unit increment to indicate a temperature *interval* (a difference between two temperatures or an uncertainty). "Celsius" is named after the Swedish astronomer Anders Celsius (1701 – 1744), who developed a similar temperature scale two years before his death.

•

•From 1744 until 1954, 0 °C on the Celsius scale was defined as the freezing point of water and 100 °C was defined as the boiling point of water under a pressure of one standard atmosphere; this close equivalency is taught in schools today.

•This definition also precisely relates the Celsius scale to the Kelvin scale, which is the SI base unit of temperature (symbol: K). Absolute zero—the temperature at which no energy remains in a substance—is defined as being precisely 0 K *and* −273.15 °C. The triple point of water is defined as being precisely 273.16 K *and* 0.01 °C

- Throughout the world, except in the U.S. and a few other countries the Celsius temperature scale is used for practically all purposes. The only exceptions are some specialist fields (e.g., low-temperature physics, astrophysics, light temperature in photography) where the closely related Kelvin scale dominates instead. Even in the U.S., almost the entire scientific world and most engineering fields, especially high-tech ones, use the Celsius scale. The general U.S. population (remains more accustomed to the Fahrenheit scale, which is therefore the scale that most U.S. broadcasters use in weather forecasts.
- The Fahrenheit scale is also commonly used in the U.S. for body temperatures.
- The United Kingdom has almost exclusively used the Celsius scale since the 1970s (but it is often called *centigrade*). A notable exception is that some broadcasters and publications still quote Fahrenheit air temperatures in weather forecasts (especially during summer), for the benefit of generations born before about 1950, and air-temperature thermometers sold still show both scales for the same reason.



Fahrenheit Scale

•**Fahrenheit** is a temperature scale named after Daniel Gabriel Fahrenheit (1686–1736), the German physicist who proposed it in 1724.
In this scale, the freezing point of water is 32 degrees Fahrenheit (°F) and the boiling point 212 °F, placing the boiling and freezing points of water exactly 180 degrees apart. A degree on the Fahrenheit scale is 1/180th part of interval between the ice point and steam point or boiling point. On the Celsius scale, the freezing and boiling points of water are exactly 100 degrees apart, thus the unit of this scale. A temperature interval of one degree Fahrenheit is an interval of 5⁄9 of a degree Celsius. The Fahrenheit and Celsius scales coincide at −40 degrees (i.e. *−40 °F* and *−40 °C* describe the same temperature).

Fahrenheit temperature conversion formulae

	from Fahrenheit	to Fahrenheit
Celsius	$[°C] = ([°F] - 32) \times {}^{5}\!/_{9}$	$[°F] = [°C] \times {}^{9}\!/_{5} + 32$
Kelvin	$[K] = ([°F] + 459.67) \times {}^{5}\!/_{9}$	$[°F] = [K] \times {}^{9}\!/_{5} - 459.67$

For temperature *intervals* rather than specific temperatures,

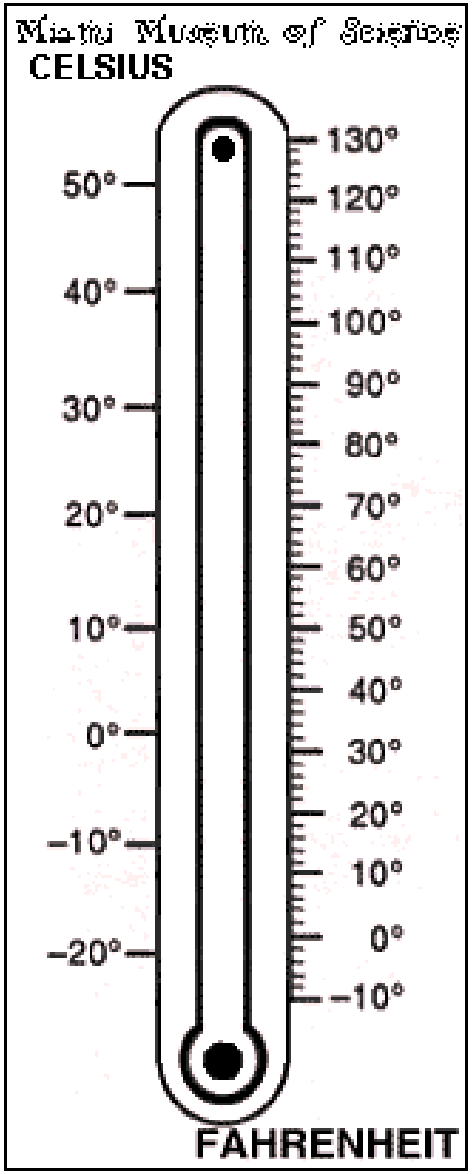
1 °F = 1 °R

and

$1\ °F = {}^{5}\!/_{9}\ °C$

Usage

- The Fahrenheit scale was the primary temperature standard for climatic, industrial and medical purposes in most English-speaking countries until the 1960s.
- In the late 1960s and 1970s, the Celsius (formerly *Centigrade*) scale was phased in by governments as part of the standardizing process of metrication.
- Only in the United States and a few other countries the Fahrenheit system continues to be the accepted standard for non-scientific use. Most other countries have adopted Celsius as the primary scale in all use. Fahrenheit is sometimes used by older generations in English speaking countries, especially for measurement of higher temperatures and for cooking.



Kelvin Scale

•The **kelvin** (symbol: **K**) is a unit increment of temperature and is one of the seven SI base units. The **Kelvin scale** is a thermodynamic (absolute) temperature scale where absolute zero, the theoretical absence of all thermal energy, is zero (0 K).

•The Kelvin scale and the kelvin are named after the British physicist and engineer William Thomson, 1st Baron Kelvin (1824–1907), who wrote of the need for an “absolute thermometric scale”.

•The kelvin unit and its scale exactly relate to the Celsius scale. Absolute zero—the temperature at which nothing could be colder and no heat energy remains in a substance—is, by definition, exactly 0 K *and* −273.15 °C. The triple point of water is, by definition, exactly 273.16 K *and* 0.01 °C. This definition does three things:

It fixes the magnitude of the kelvin unit as being exactly 1 part in 273.16 of the difference between absolute zero and the triple point of water;

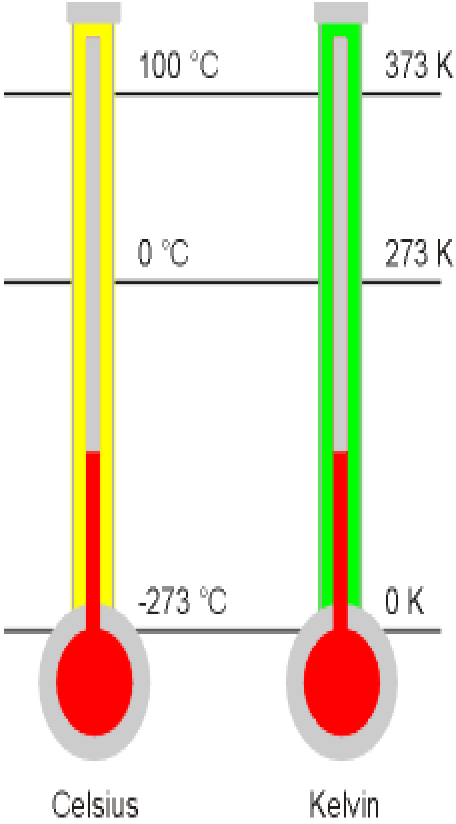
It establishes that one kelvin has exactly the same magnitude as a one-degree increment on the Celsius scale; and

It establishes the difference between the two scales’ null points as being exactly 273.15 kelvins (0 K ≡ −273.15 °C and 273.16 K ≡ 0.01 °C). Temperatures in kelvin can be converted to other units per the table at bottom left.

Kelvin temperature conversion formulae

	from Kelvin	to Kelvin
Celsius	$[°C] = [K] - 273.15$	$[K] = [°C] + 273.15$
Fahrenheit	$[°F] = [K] \times \frac{9}{5} - 459.67$	$[K] = ([°F] + 459.67) \times \frac{5}{9}$

For temperature *intervals* rather than specific temperatures,
1 K = 1 °C
and
1 K = 1.8 °R



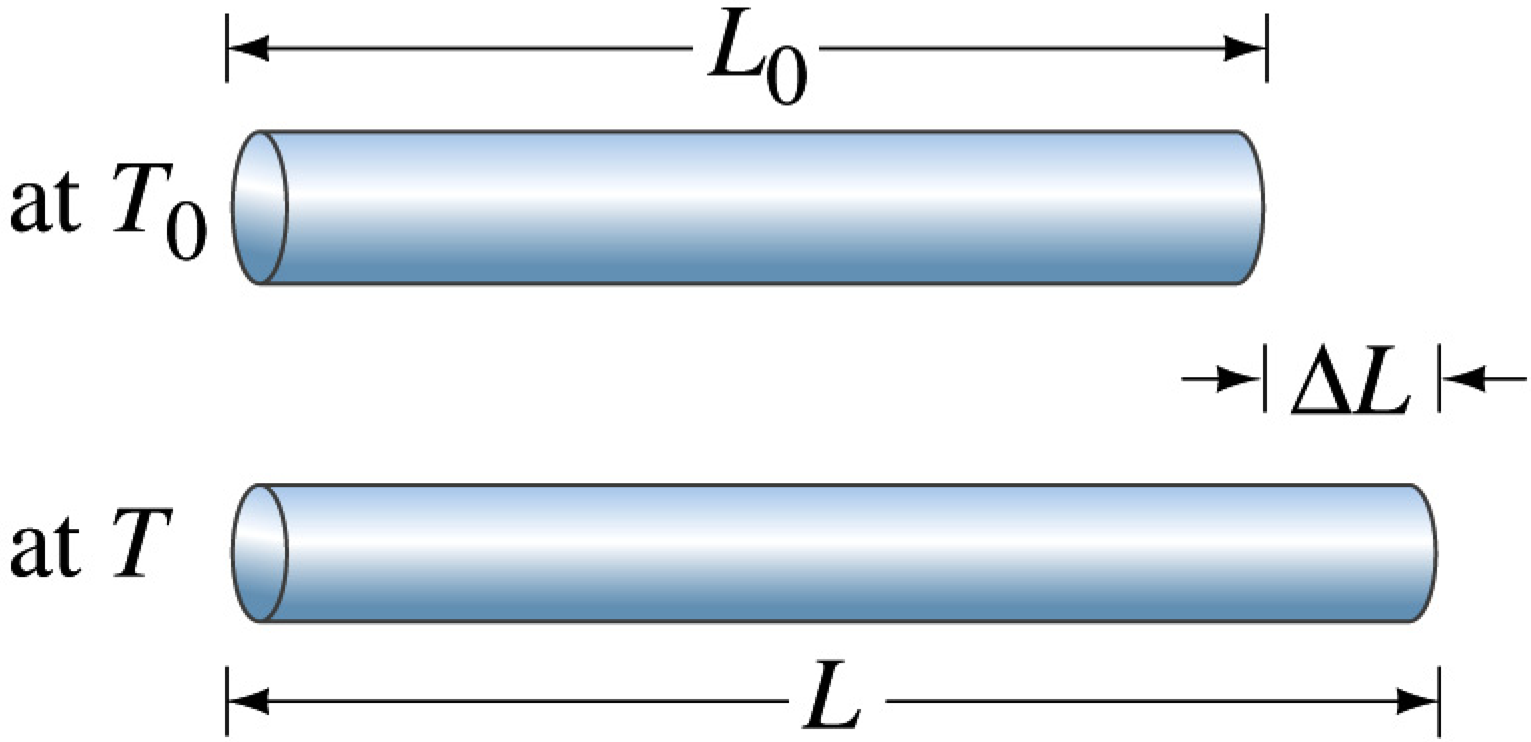
Thermal Expansion

Linear Expansion

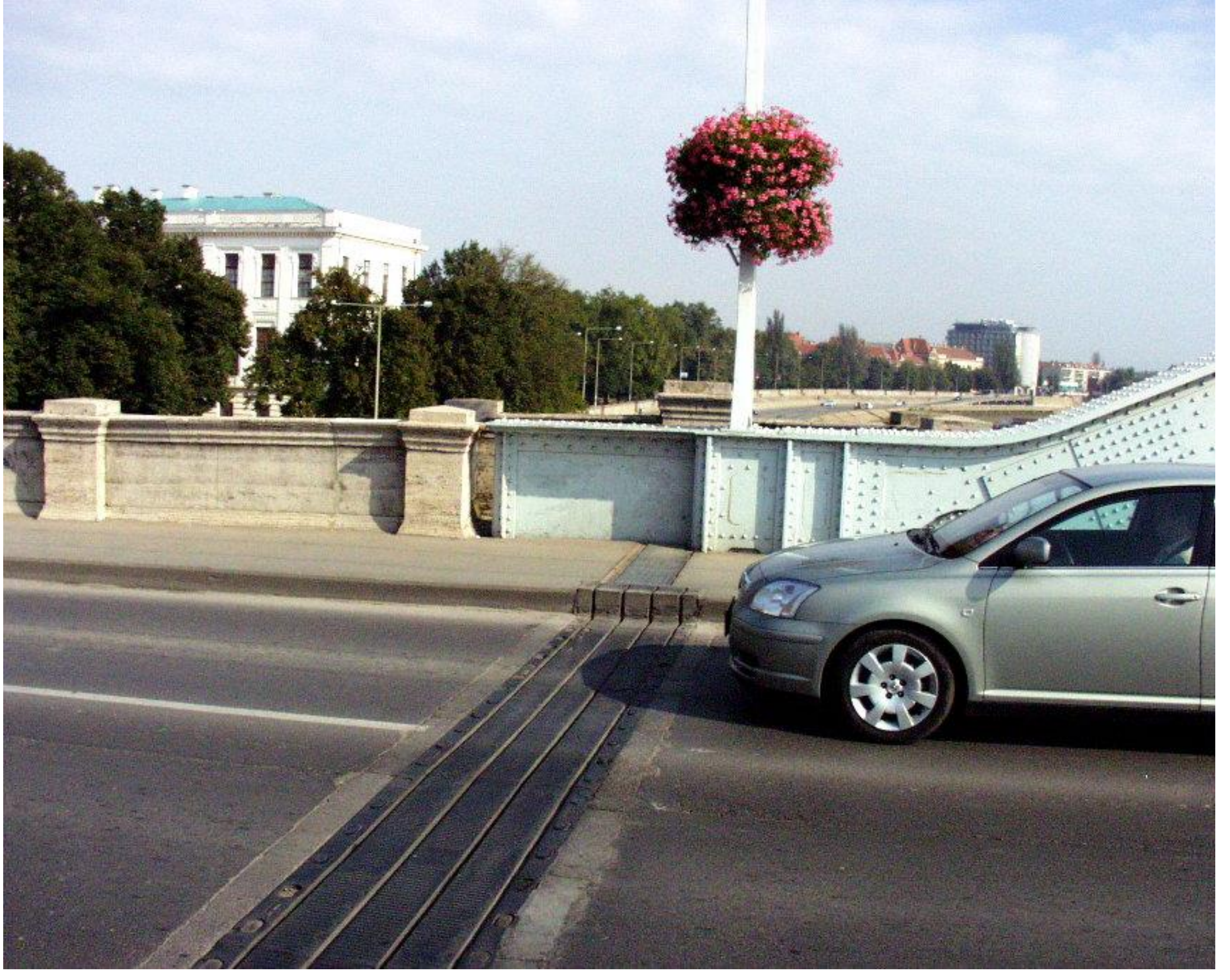
$$\Delta L = \alpha L_o \Delta T$$

where α is the coefficient of linear expansion. Its units are $(C^o)^{-1}$.

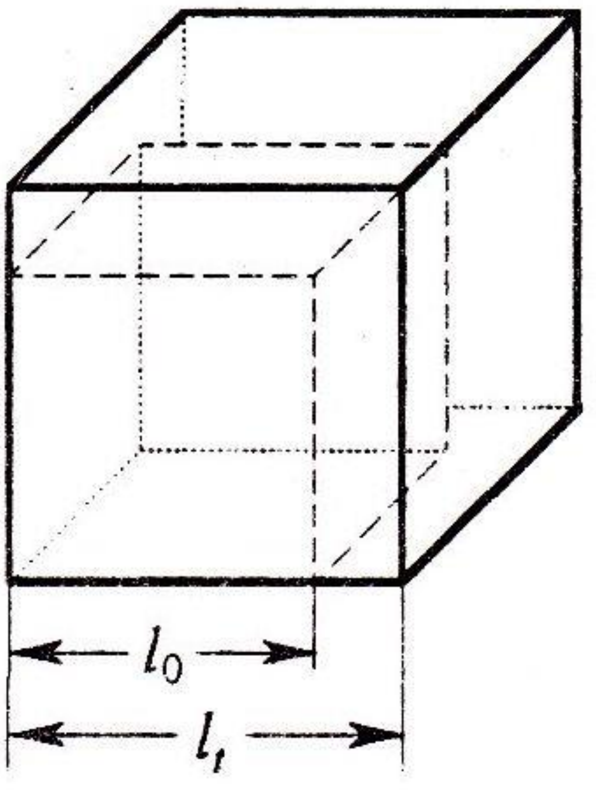
This equation is empirical.



L_0
at T_0
ΔL
at T
L



Thermal Volume Expansion



$$l_t = l_0\left[1 + \alpha\left(T - T_0\right)\right]$$

$$V_t = l_t^{\;3} = l_0^{\;3}\left[1 + \alpha\left(T - T_0\right)\right]^3$$

$$V_t \approx V_0\left[1 + 3\alpha\left(T - T_0\right)\right]$$

$$\boxed{V_t = V_0\left[1 + \beta\left(T - T_0\right)\right]}$$

Thermal Expansion

Volume Expansion

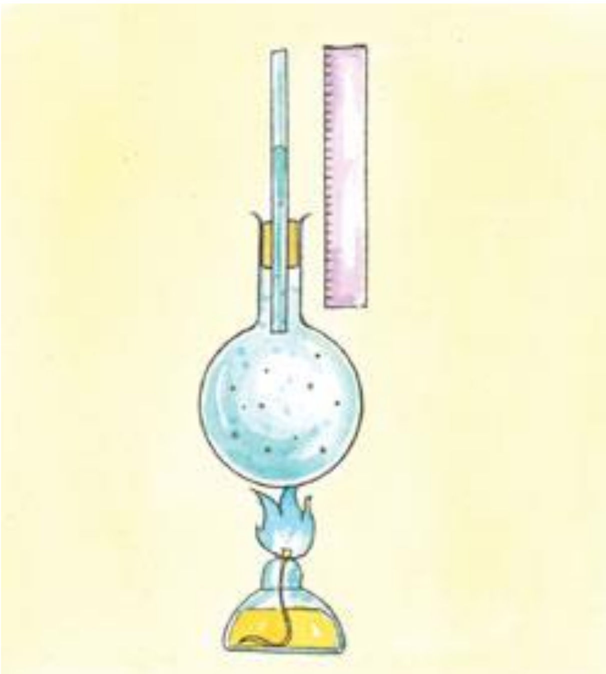
$$\Delta V = \beta V_o \Delta T$$

where β is the coefficient of volume expansion.

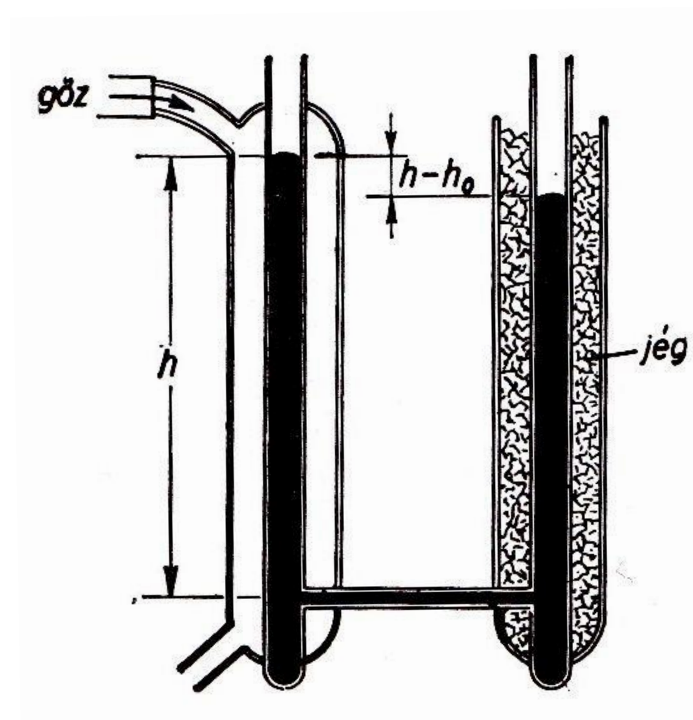
Note: $\beta \approx 3\alpha$.

The units of β are $(C^o)^{-1}$.

Thermal expansion of liquids



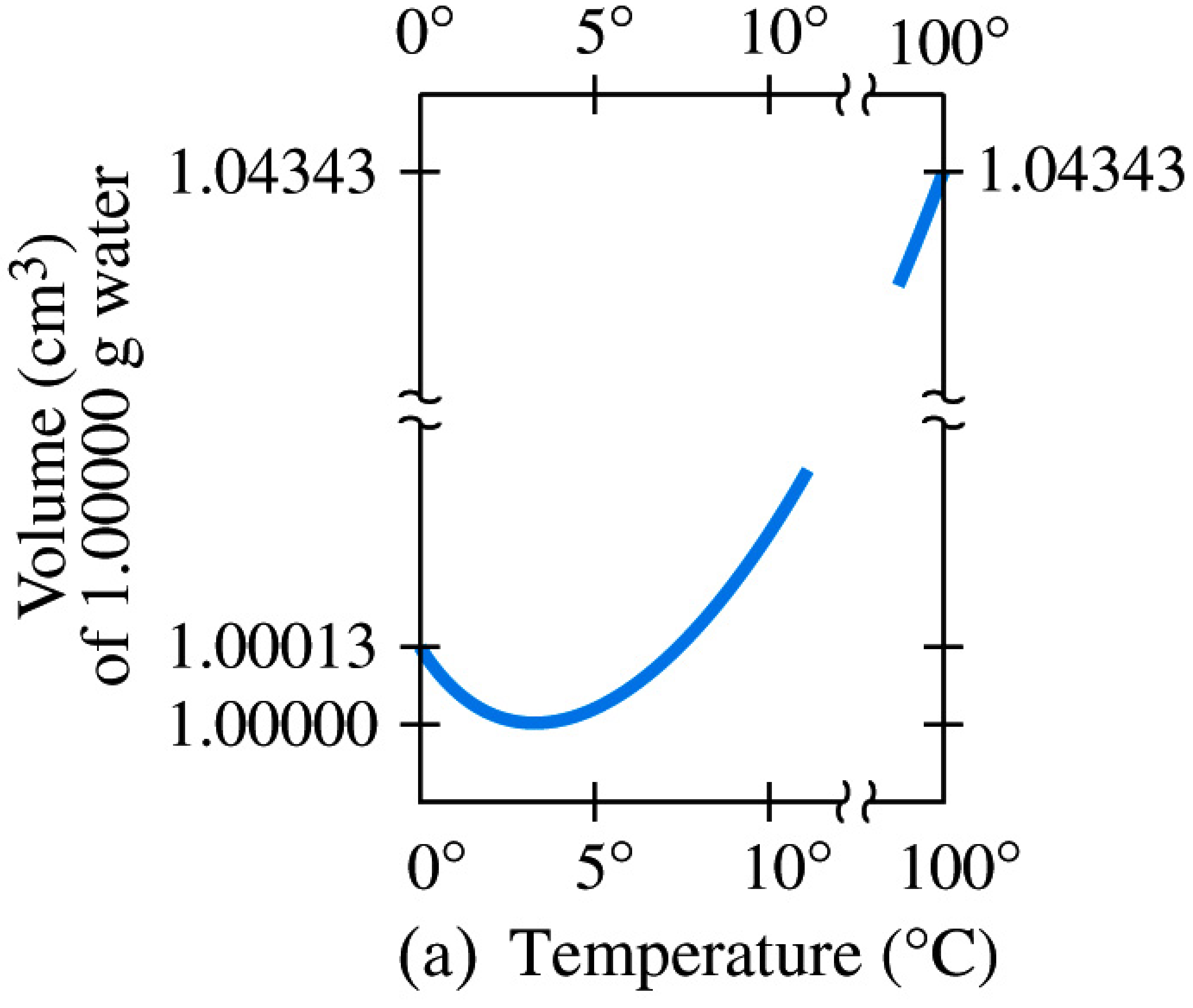
$$V_t = V_0\left[1 + \beta\left(T - T_0\right)\right]$$



$$\rho = \frac{\rho_0}{1 + \beta\left(T - T_0\right)}$$

Anomalous Behavior of Water Below 4^oC

- Most substances expand more or less uniformly with an increase in temperature (as long as no phase change occurs).
- Water, however, does not follow the usual pattern.
- If water at 0^o C is heated, it actually decreases in volume until it reaches 4^o C.
- Above 4^o C water behaves normally.


0°
5°
10°
100°
1.04343
1.04343
Volume (cm^3)
of 1.00000 g water
1.00013
1.00000
0°
5°
10°
100°
(a) Temperature (°C)

What does Boyle's Law mean?

p * V = constant

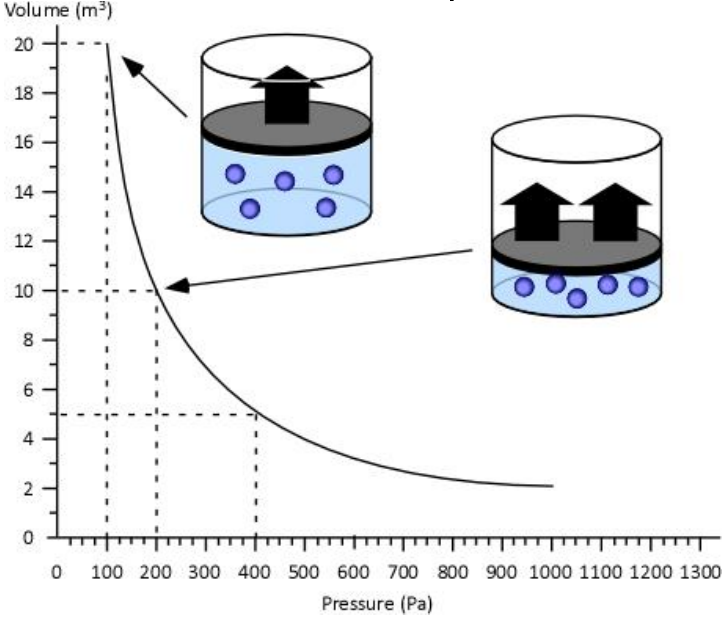
Suppose you have a cylinder with a piston in the top so you can change the **volume**. The cylinder has a gauge to measure **pressure**, is contained so the **amount** of gas is constant, and can be maintained at a constant **temperature**.

A decrease in volume will result in increased pressure. Boyle's Law can be used to predict the interaction of pressure and volume.

If you know the initial pressure and volume, and have a target value for one of those variables, you can predict what the other will be for the same amount of gas under constant temperature.

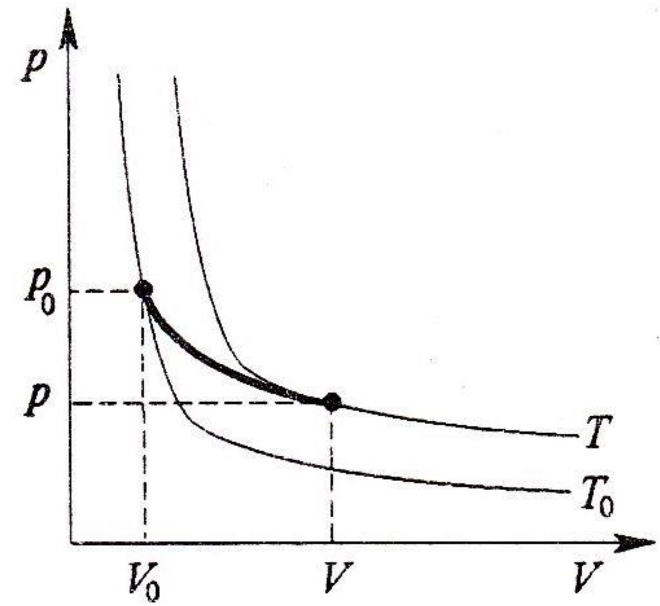
$p_1 * V_1 = p_2 * V_2$

Boyle's Law



General Gas Law

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$



$$\frac{pV}{T} = \frac{p_0 V_0}{T_0} = constant$$

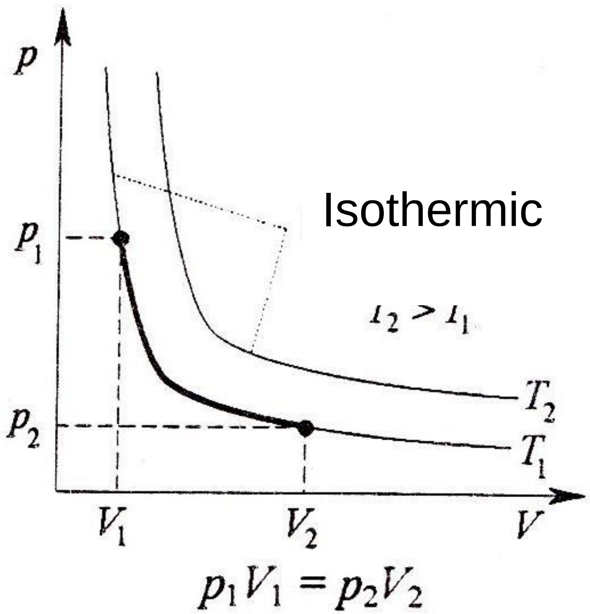
Gas Law Relationships

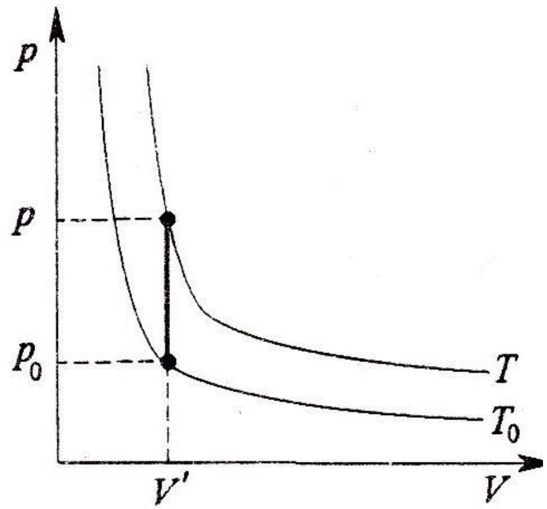
Expression of gas laws	Fixed values	Variable relationships	Form for calculations
PV = constant	n, T	Inverse	$P_1V_1 = P_2V_2$
V/T = constant	n, P	Direct	$V_1/T_1 = V_2/T_2$
P/T = constant	n, V	Direct	$P_1/T_1 = P_2/T_2$

$$pV = nRT$$

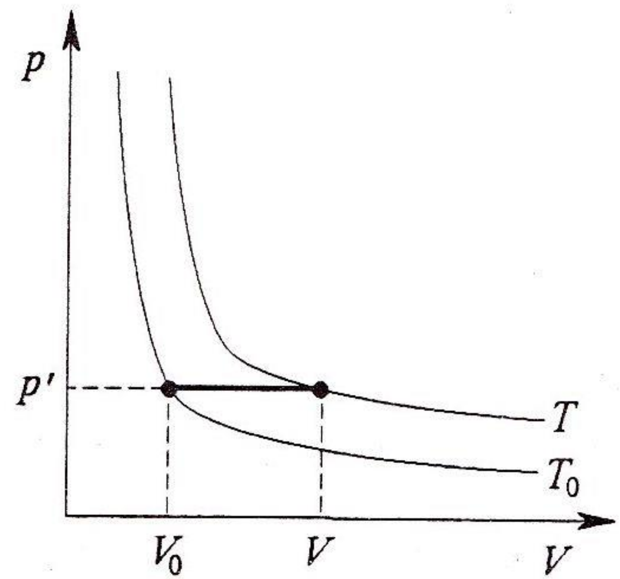
$$pV = NkT$$

Specific considerations





isovolumetric

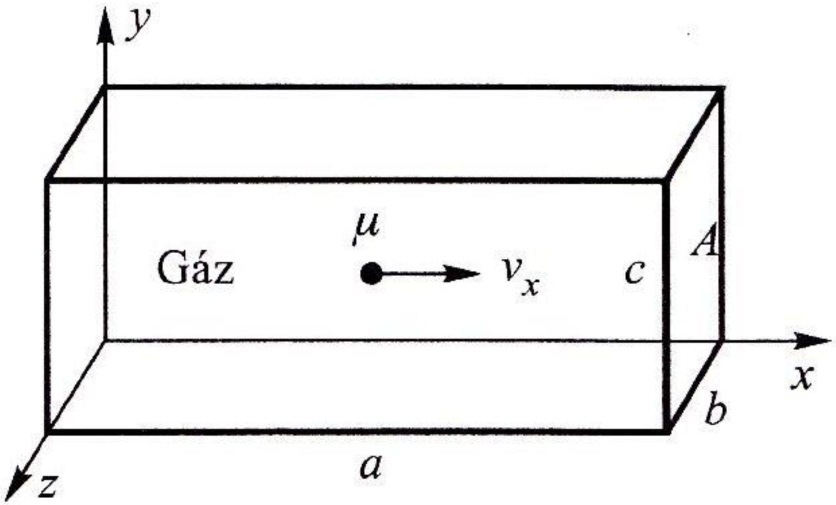


isobaric

The Kinetic Theory – Molecular Theory of Gases

- Microscopic view of gases is called the **kinetic theory of gases** and assumes that
  - Gas is collection of molecules (atoms) in continuous random motion.
  - The molecules are infinitely small point-like particles that move in straight lines until they collide with something.
  - Gas molecules do not influence each other except during collision.
  - All collisions are elastic; the total kinetic energy is constant at constant T.
  - Average kinetic energy is proportional to T.

The Kinetic Theory



$$pA = F = \frac{\mathrm{d}I}{\mathrm{d}\tau}$$

How many collosions? $Av_{x\ avr}\,\mathrm{d}\tau$

$$I(v_x) = N\mu v_x$$

$$\mathrm{d}I(v_x) = \mathrm{d}N\,2\mu v_x$$

$$\overline{v_x^{\ 2}} = \overline{v_y^{\ 2}} = \overline{v_z^{\ 2}} \qquad \overline{v^2} = 3\overline{v_x^{\ 2}}$$

The average kinetic energy of the molecule is $\bar{\varepsilon}_k = \frac{1}{2}\mu\overline{v^2} = \frac{3}{2}kT$

$$p = \frac{2}{3}\frac{N}{V}\left(\frac{1}{2}\mu\overline{v^2}\right) \qquad pV = \frac{2}{3}N\bar{\varepsilon}_k$$

$$\boxed{pV = NkT}$$

The Behavior of Real Gases

- The molar volume is not constant as is expected for ideal gases.
- These deviations due to an attraction between some molecules.
- Finite molar molecular volume.
- For compounds that deviate from ideality the van der Waals equation is used:

$$\left(P + \frac{n^2 a}{V^2}\right)(V - nb) = nRT$$

  where a and b are constants that are characteristic of the gas.
- Applicable at high pressures and low temperatures.

Body temperature: How much is it? Where to measure?

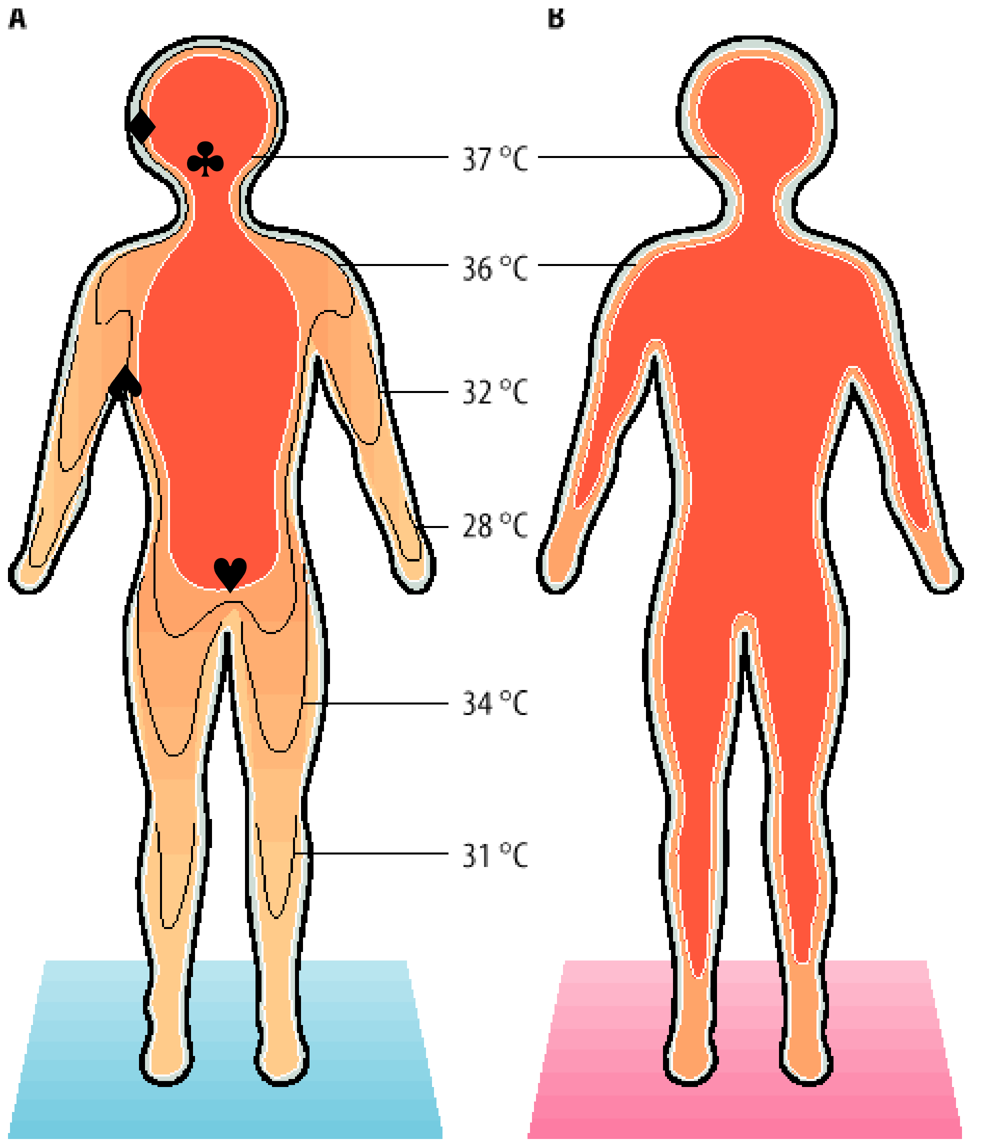


Abb. 30-3 aus Schmidt/Thews: Physiologie des Menschen 27. Auflage 1997

♦ = ear (tympanic)

♣ = sublingual (oral)

♥ = rectal

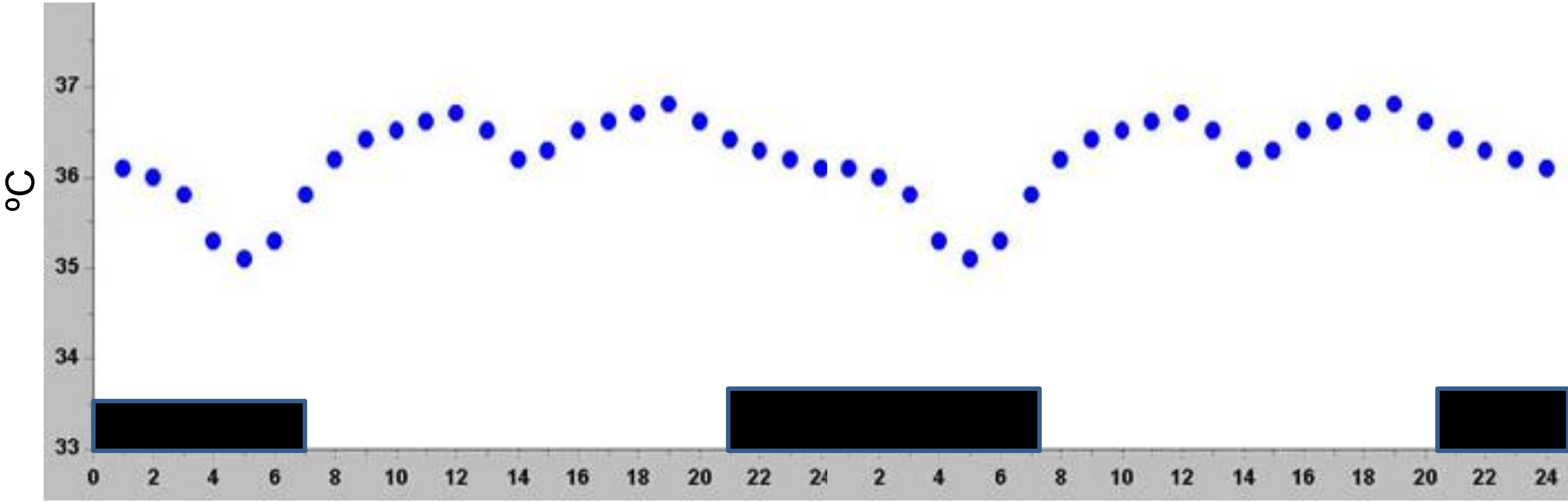
♠ = axillary

The concept of body “core” and “shell”

Only “core” temperatures are relatively constant!

The human body's temperature displays a rhythmic dayly variation

Core temperature



Influenced by:

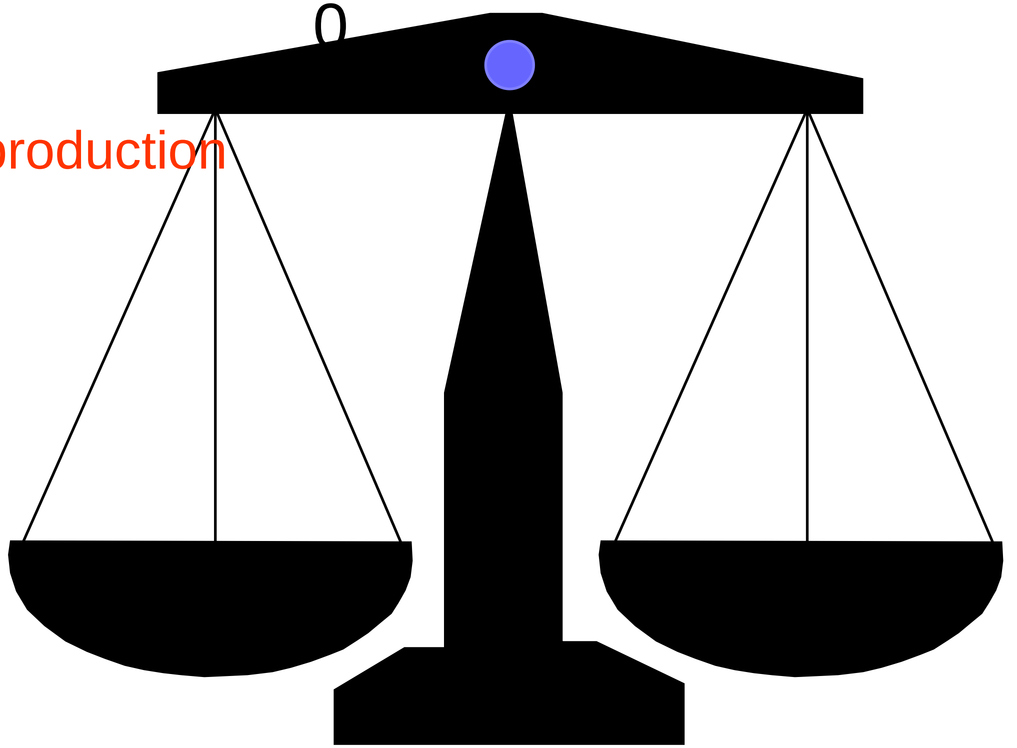
physical activity
meals (when, how much, and the composition of the food)
mental state

When there is a decrease : heat loss > heat production+heat gain

When there is an increase : heat loss < heat production+heat gain

Constant body temperature requires heat balance

Heat storage= 0



- Metabolic heat production
- Radiation*
- Conduction*
- Convection*

- Radiation*
- Conduction*
- Convection*
- Evaporation

Heat gain

Heat loss

*These mechanisms are bidirectional and can be called collectively as heat exchange mec

Heat flow

•Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact.

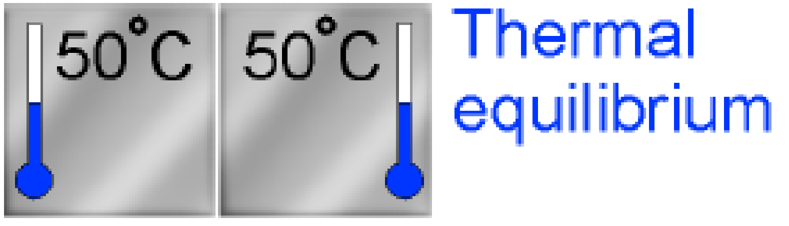
•If no heat flow occurs, the two objects have the same temperature; otherwise heat flows from the hotter object to the colder object.

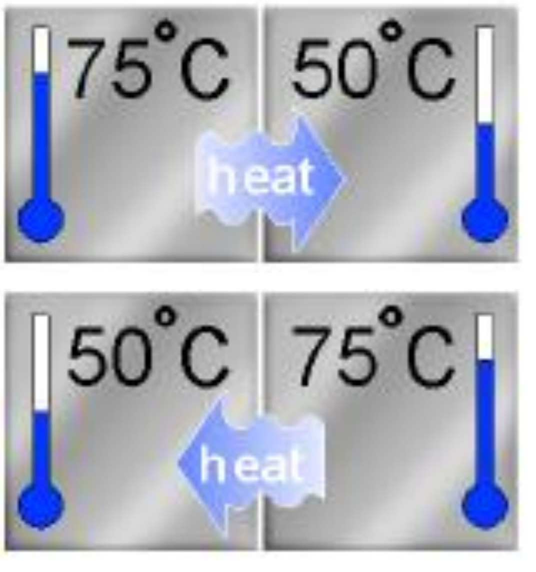
•These two basic principles are stated in the zeroth law and second law of thermodynamics, respectively.

•For a solid, these microscopic motions are principally the vibrations of its atoms about their sites in the solid.

Thermal Equilibrium

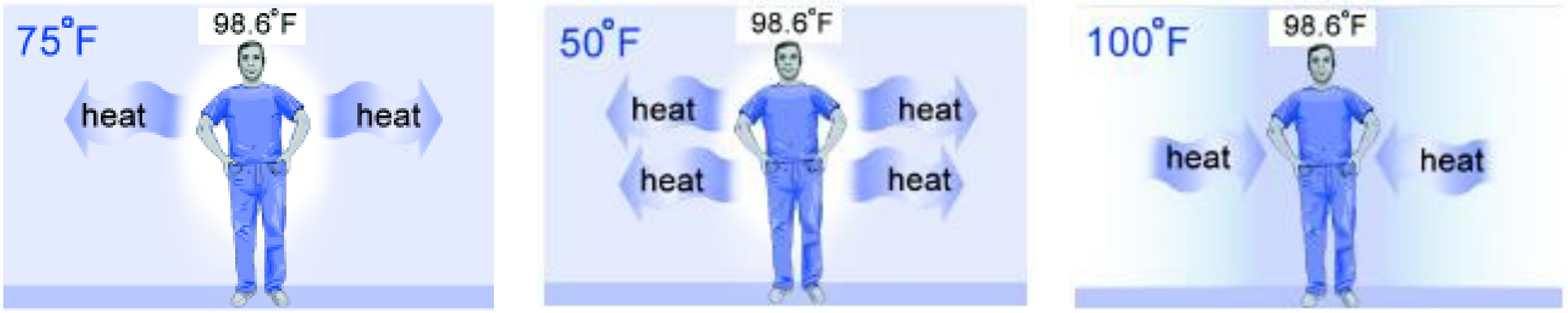
- Two bodies are in thermal equilibrium with each other when they have the same temperature.
- In nature, heat always flows from hot to cold until thermal equilibrium is reached.

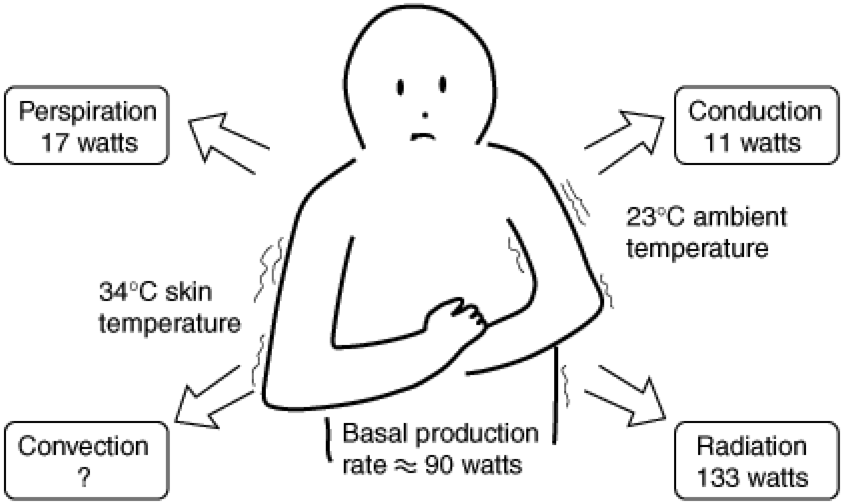




Heat Transfer

- The science of how heat flows is called heat transfer.
- There are three ways heat transfer works: conduction, convection, and radiation.
- Heat flow depends on the temperature difference.





1 watt=1 J/s

Basal heat production =
90J/sx24x 3600= 7776000J = 7760kJ
1850 kcal
This is an estimate !!!

This is a simplified model of the process by which the human body gives off heat. Even when inactive, an adult male must lose heat at a rate of about 90 watts as a result of his basal metabolism.

One implication of the model is that radiation is the most important heat transfer mechanism at ordinary room temperatures.

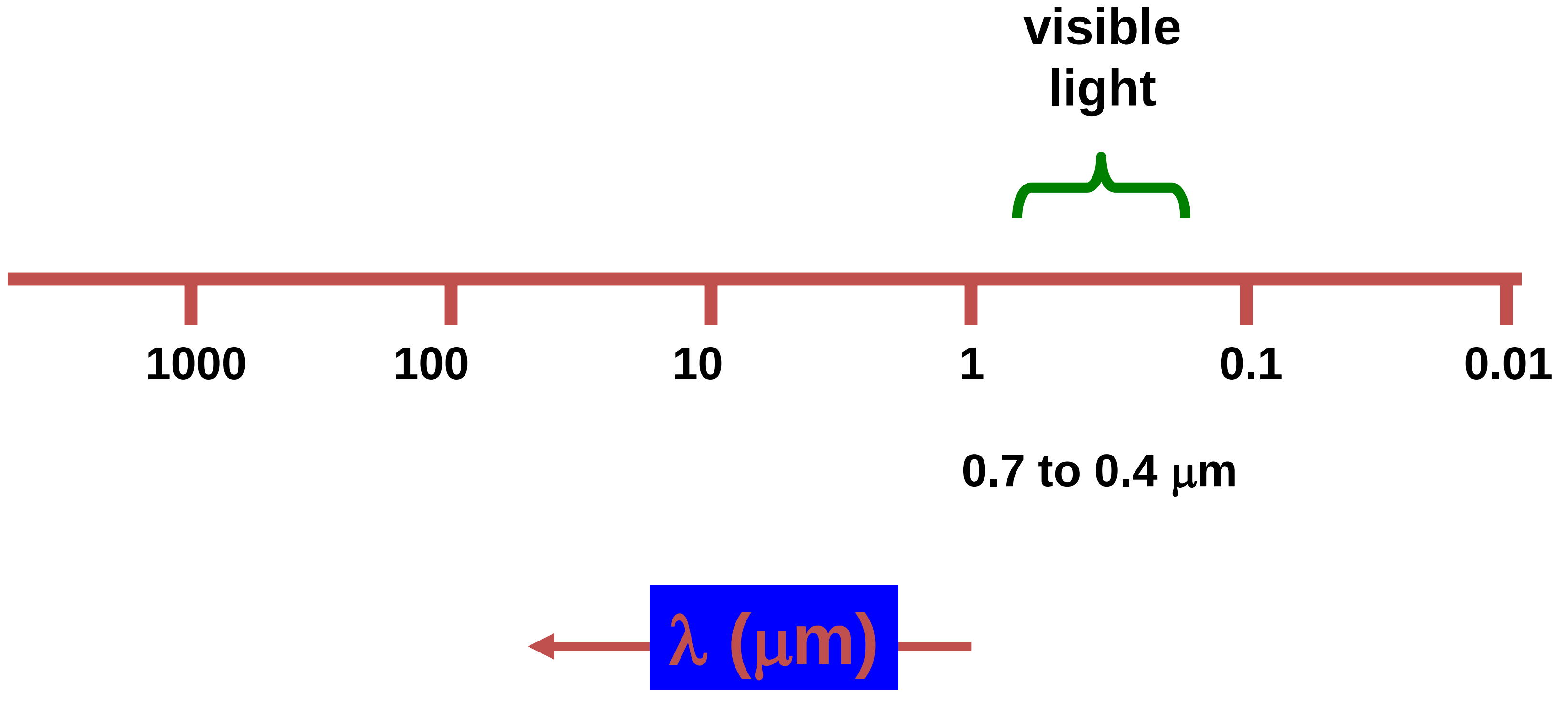
This model indicates that an unclothed person at rest in a room temperature of 23 Celsius or 73 Fahrenheit would be uncomfortably cool.

Basal Metabolic Rate (BMR)

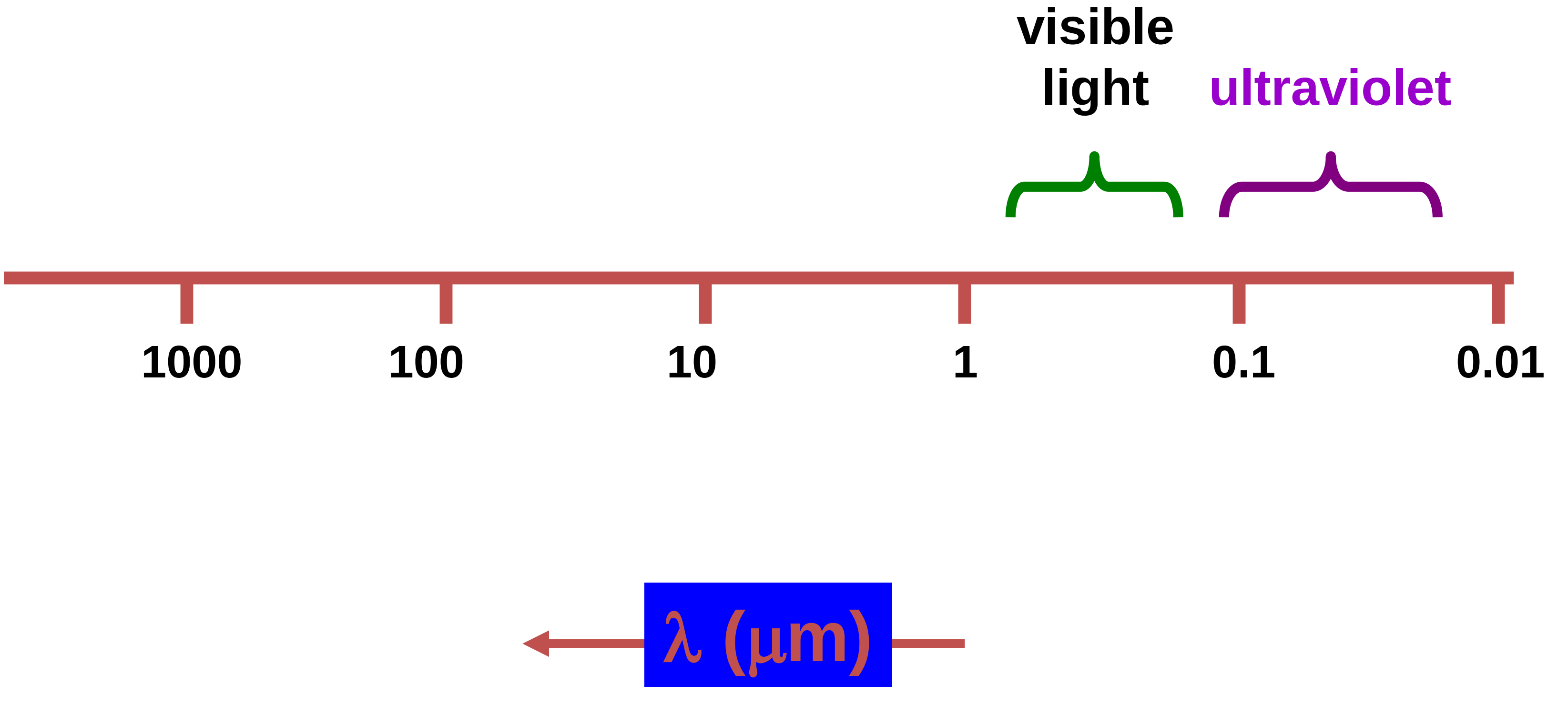
- **Basal metabolic rate** (**BMR**) is the amount of energy expended while at rest in a neutrally temperate environment, in the post-absorptive state (meaning that the digestive system is inactive, which requires about twelve hours of fasting in humans).
- Accordingly: 70 kg man BMR~1800 kcal

- Modifying factors
  - Age & gender
  - Lean muscle mass
  - Physical activity level
  - Diet
  - Hormones

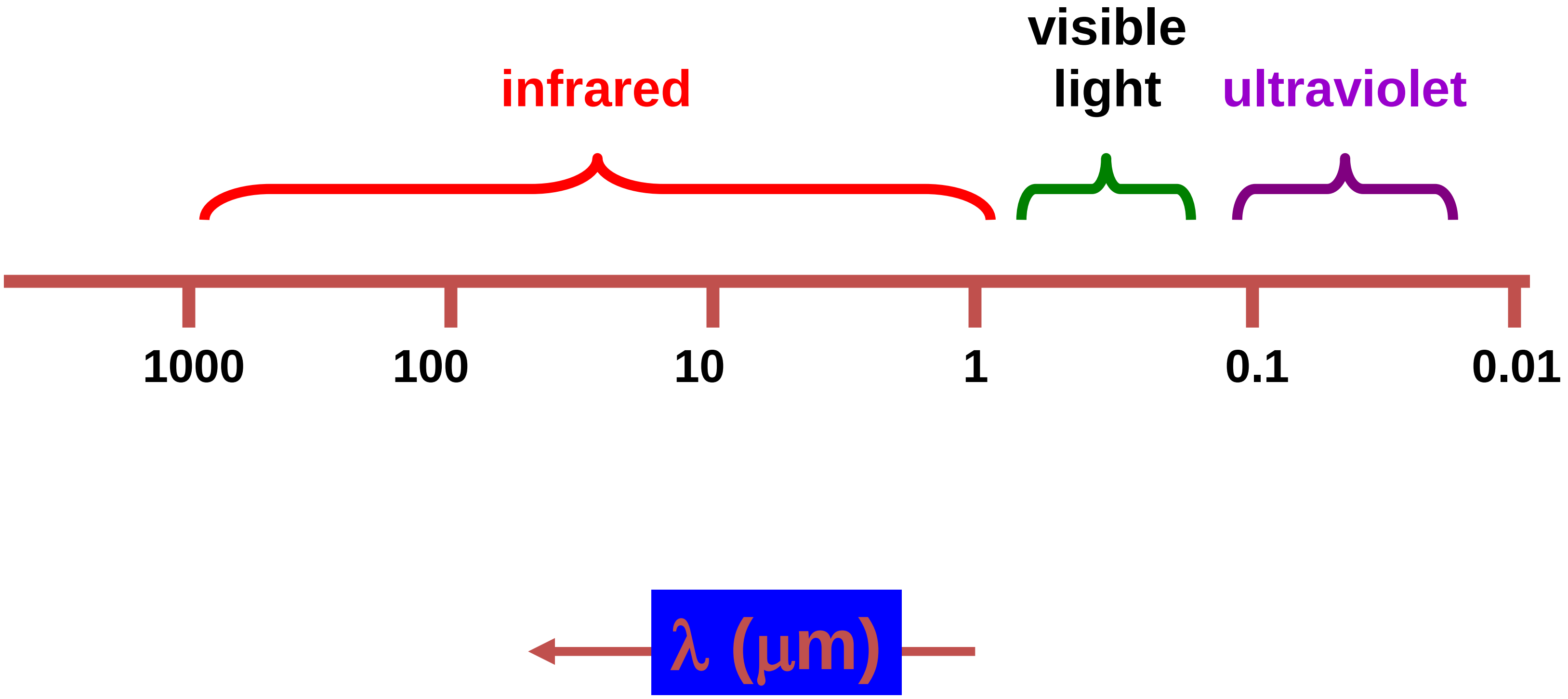
Electromagnetic Spectrum



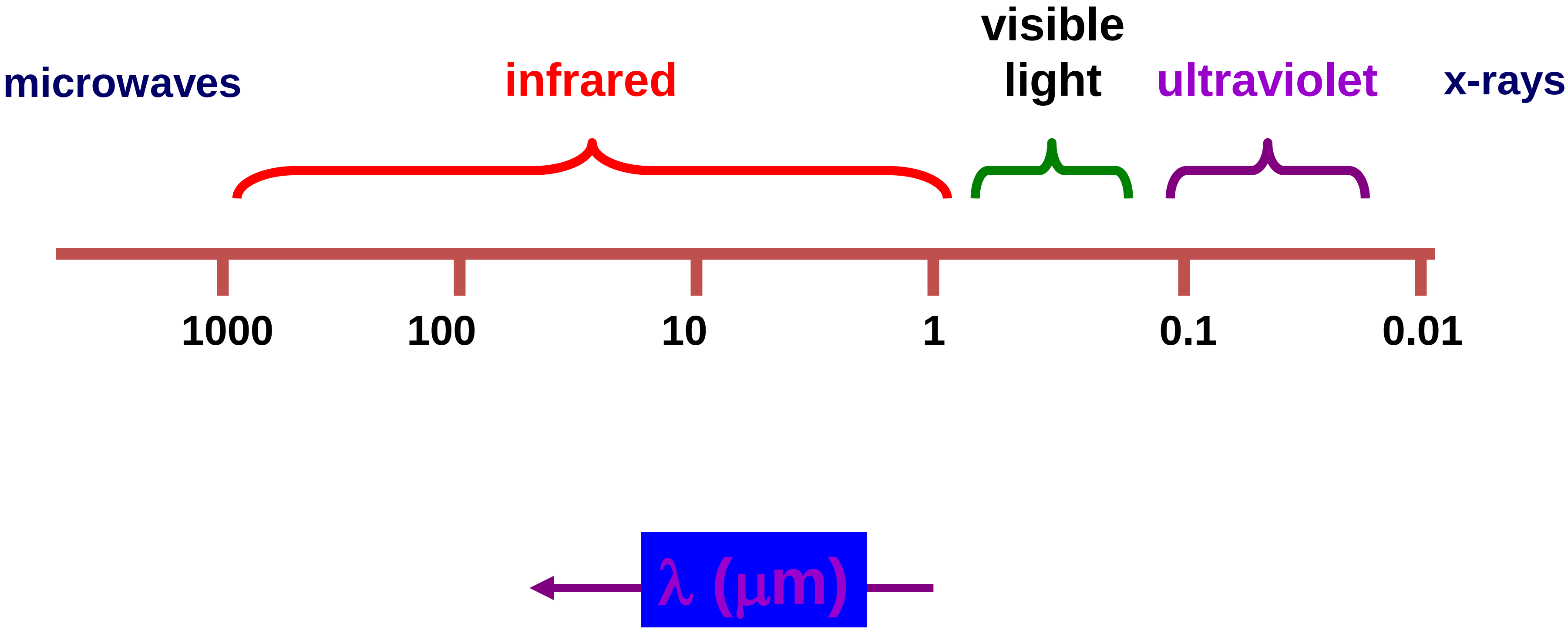
Electromagnetic Spectrum



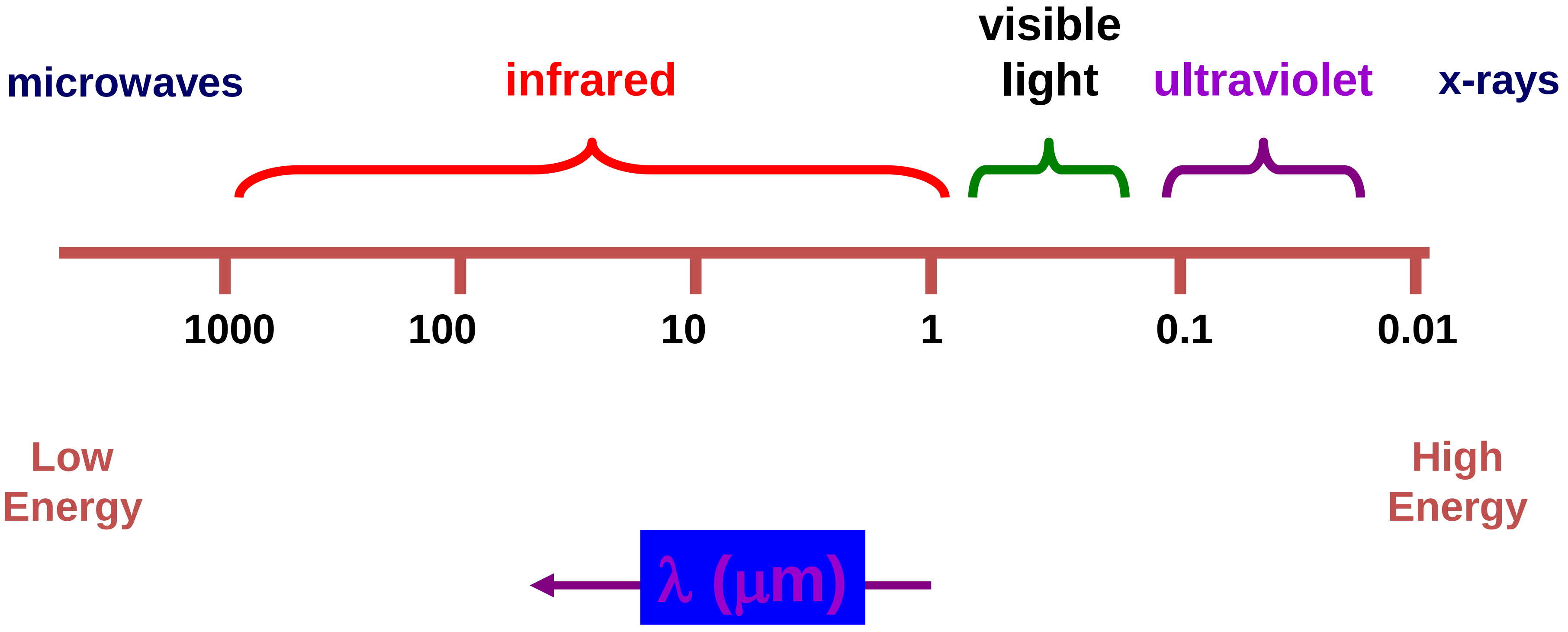
Electromagnetic Spectrum



Electromagnetic Spectrum



Electromagnetic Spectrum



Basic Laws of Radiation

1) All objects emit radiant energy.

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2) Hotter objects emit more energy than colder objects.

Basic Laws of Radiation

1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects. The amount of energy radiated is proportional to the temperature of the object.

Basic Laws of Radiation

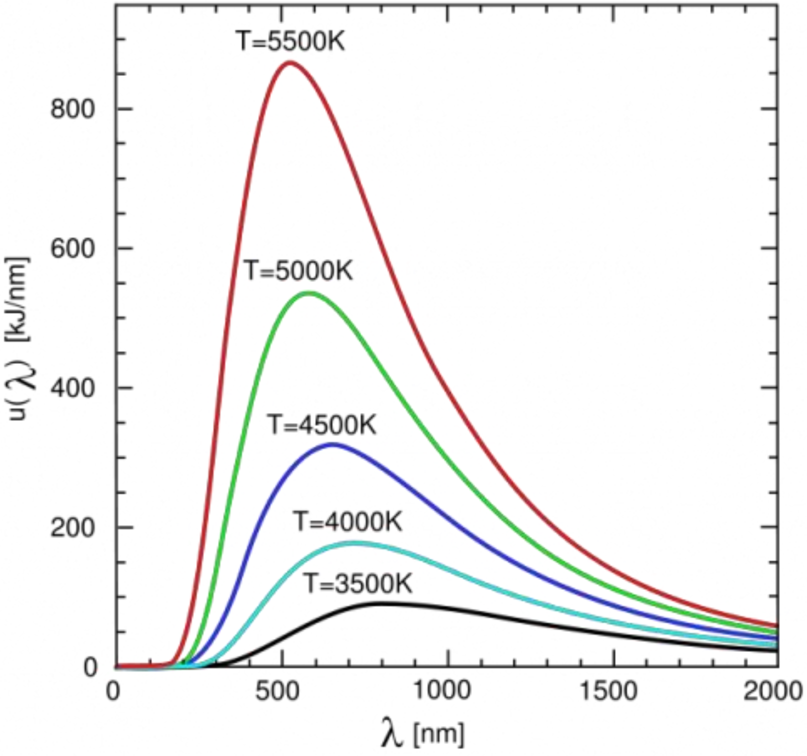
1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects. The amount of energy radiated is proportional to the temperature of the object raised to the fourth power.

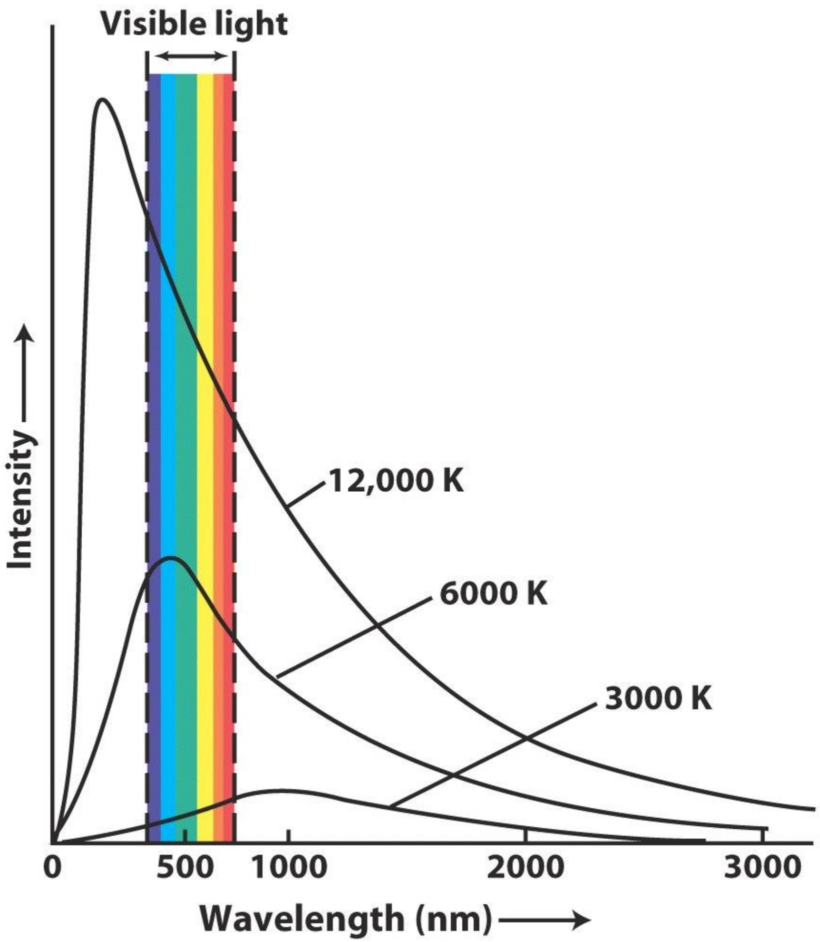
➡ This is the Stefan Boltzmann Law

$$F = \sigma T^4$$

F = flux of energy (W/m^2)
T = temperature (K)
$\sigma = 5.67 \times 10^{-8}\ W/m^2K^4$ (a constant)



Wien’s law and the Stefan-Boltzmann law are useful tools for analyzing glowing objects like stars



- A blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths
- Stars closely approximate the behavior of blackbodies, as do other hot, dense objects
- The intensities of radiation emitted at various wavelengths by a blackbody at a given temperature are shown by a blackbody curve

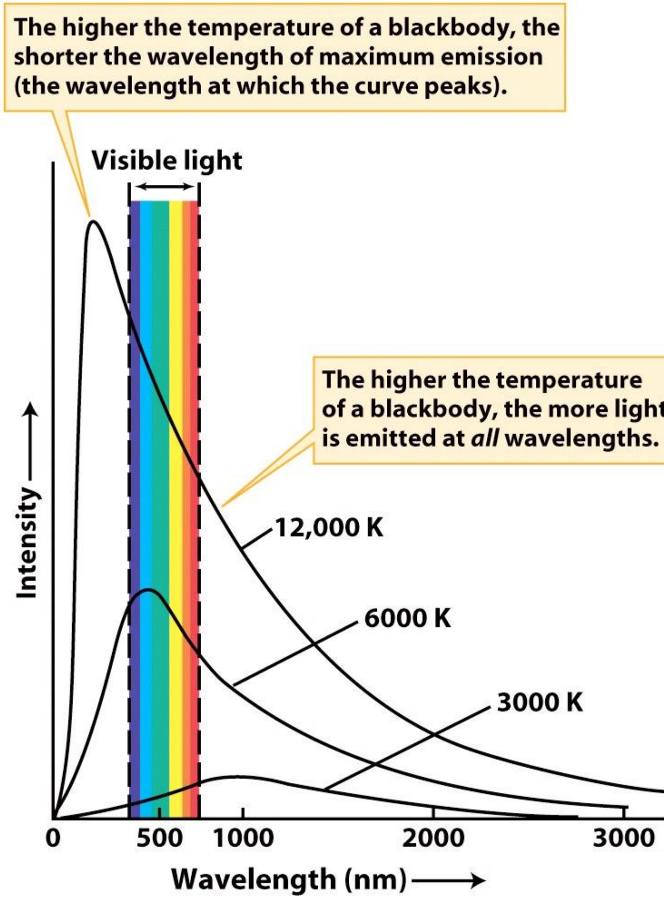
Wien's Law

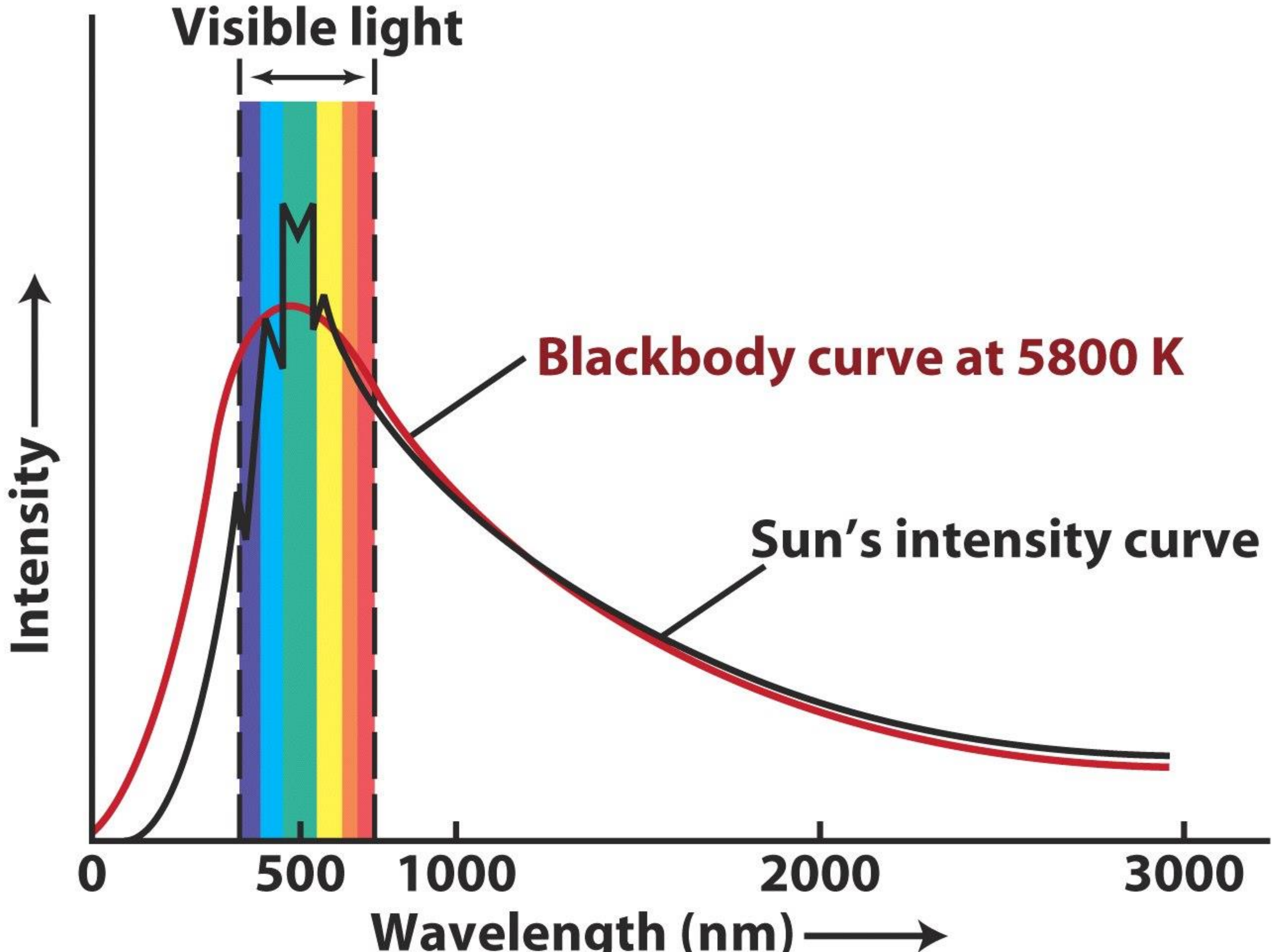
$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)

Wien's law states that the dominant wavelength at which a blackbody emits electromagnetic radiation is inversely proportional to the Kelvin temperature of the object




Visible light
Blackbody curve at 5800 K
Sun's intensity curve
Intensity
0
500
1000
2000
3000
Wavelength (nm)

Stefan-Boltzmann Law

- The Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux *E* directly proportional to the fourth power of the Kelvin temperature *T* of the object:

$$E = \sigma T^4$$

Basic Laws of Radiation

1) All objects emit radiant energy.

2) Hotter objects emit more energy than colder objects (per unit area). The amount of energy radiated is proportional to the temperature of the object.

3) The hotter the object, the shorter the wavelength (λ) of emitted energy.

Basic Laws of Radiation

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➡This is Wien's Law

$$\lambda_{max} \cong \frac{3000\ \mu m}{T(K)}$$

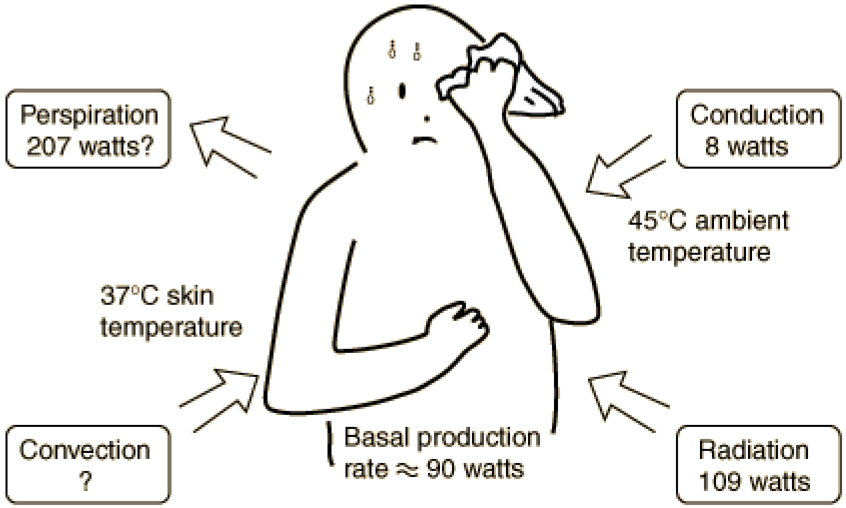
- Stefan Boltzmann Law.

$$F = \sigma T^4$$

F = flux of energy (W/m^2)
T = temperature (K)
σ = 5.67 x 10^{-8} W/m^2K^4 (a constant)

- Wien's Law

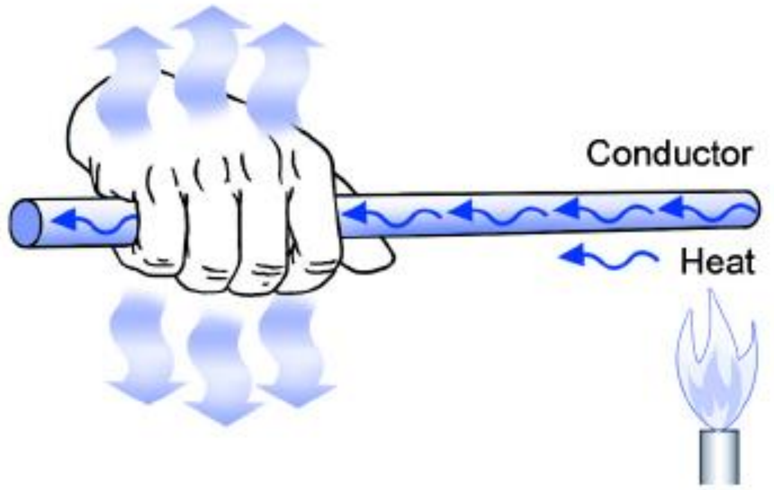
$$\lambda_{max} \cong \frac{3000\ \mu m}{T(K)}$$



What happens if the ambient temperature rises to 45 ºC ?

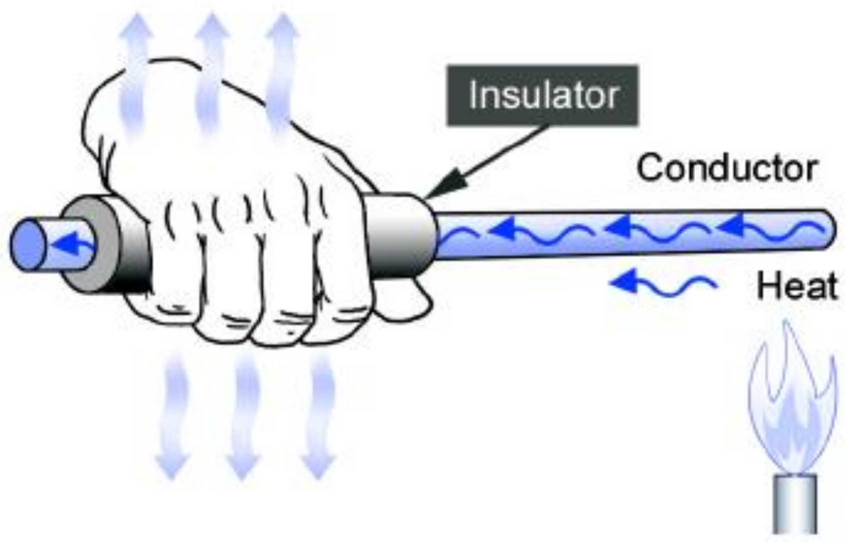
Heat Conduction

- Conduction is the transfer of heat through materials by the direct contact of matter.
- Dense metals like copper and aluminum are very good thermal conductors.



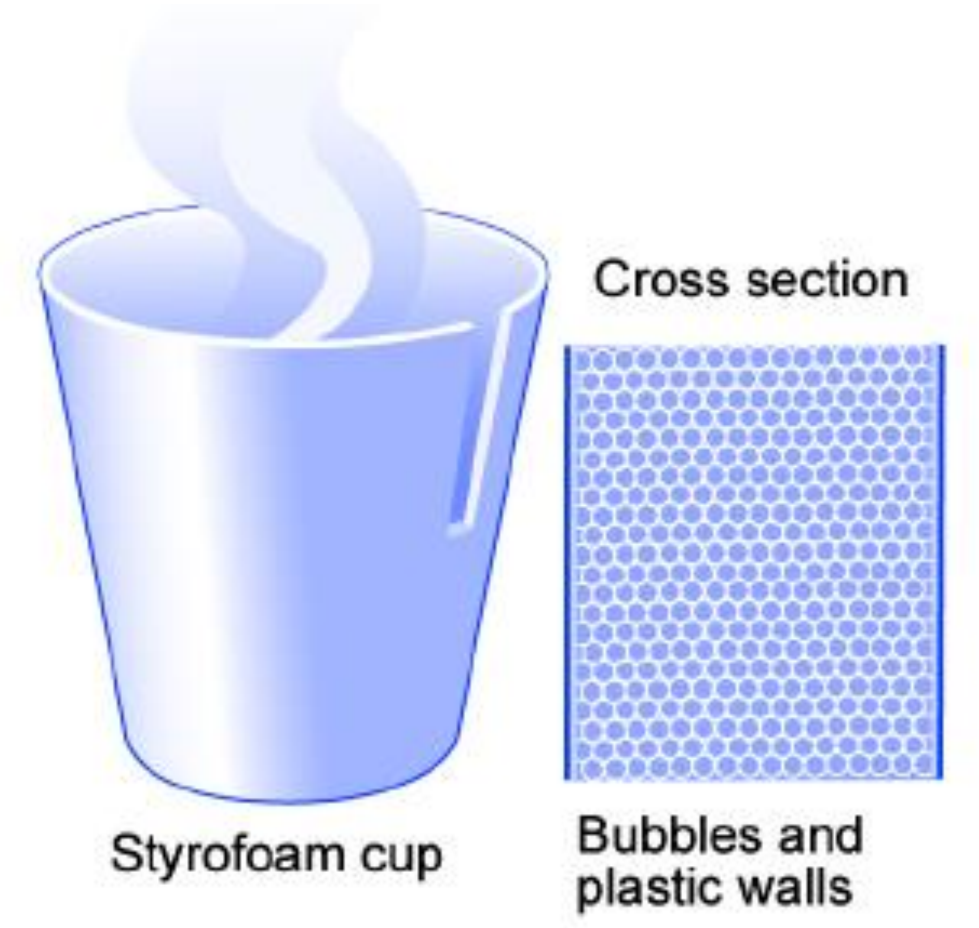
Heat Conduction

- A thermal insulator is a material that conducts heat poorly.
- Heat flows very slowly through the plastic so that the temperature of your hand does not rise very much.



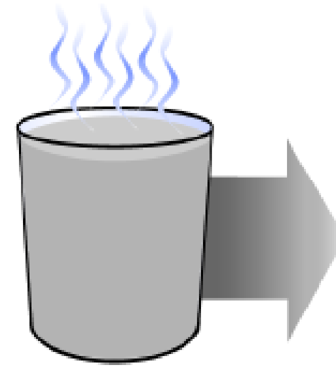
Heat Conduction

- Styrofoam gets its insulating ability by trapping spaces of air in bubbles.
- Solids usually are better heat conductors than liquids, and liquids are better conductors than gases.



Heat Conduction

- The ability to conduct heat often depends more on the structure of a material than on the material itself.
  - Solid glass is a thermal conductor when it is formed into a beaker or cup.
  - When glass is spun into fine fibers, the trapped air makes a thermal insulator.



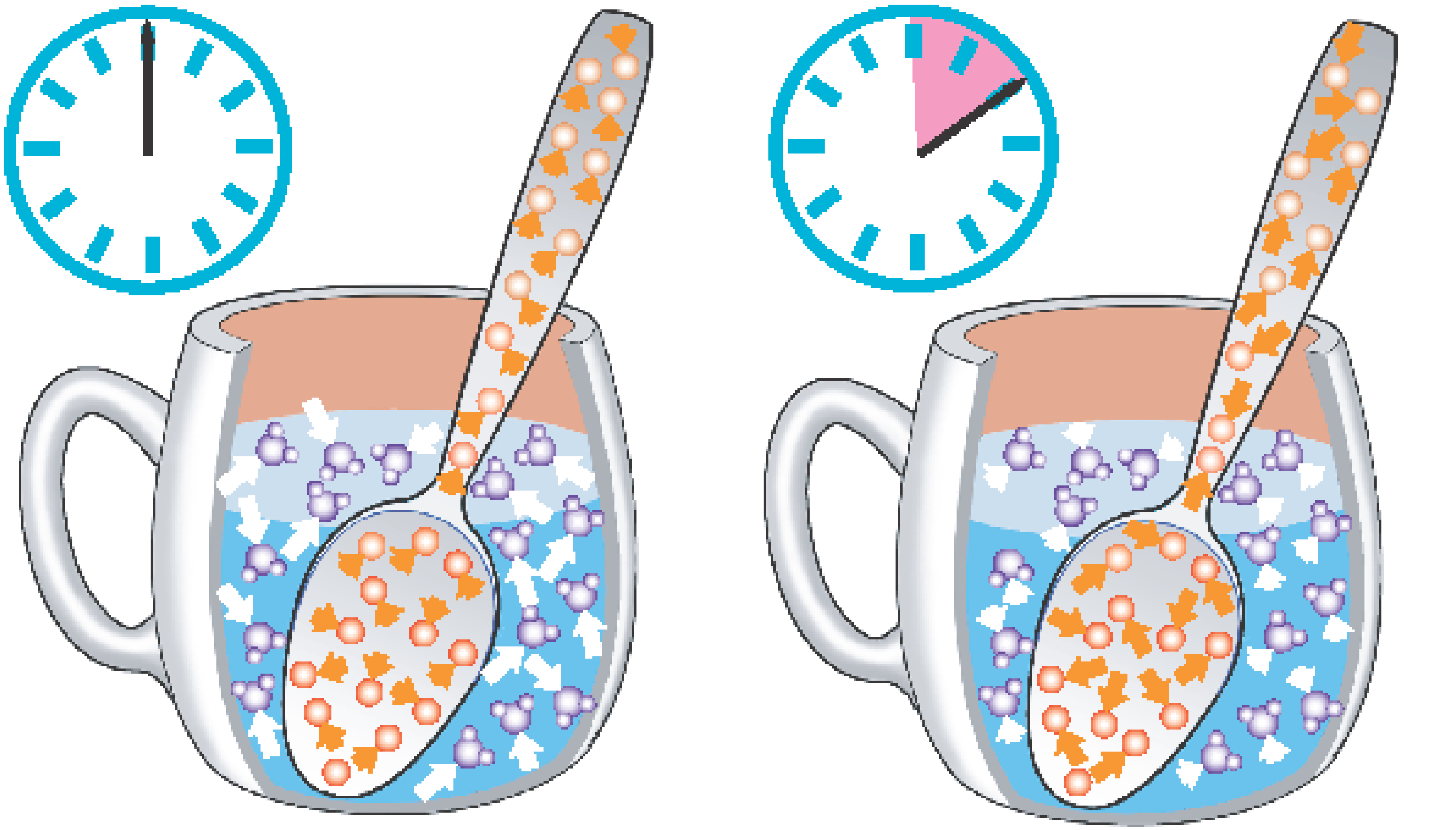
GLASS

Fiberglass insulation

Fibers and airspaces

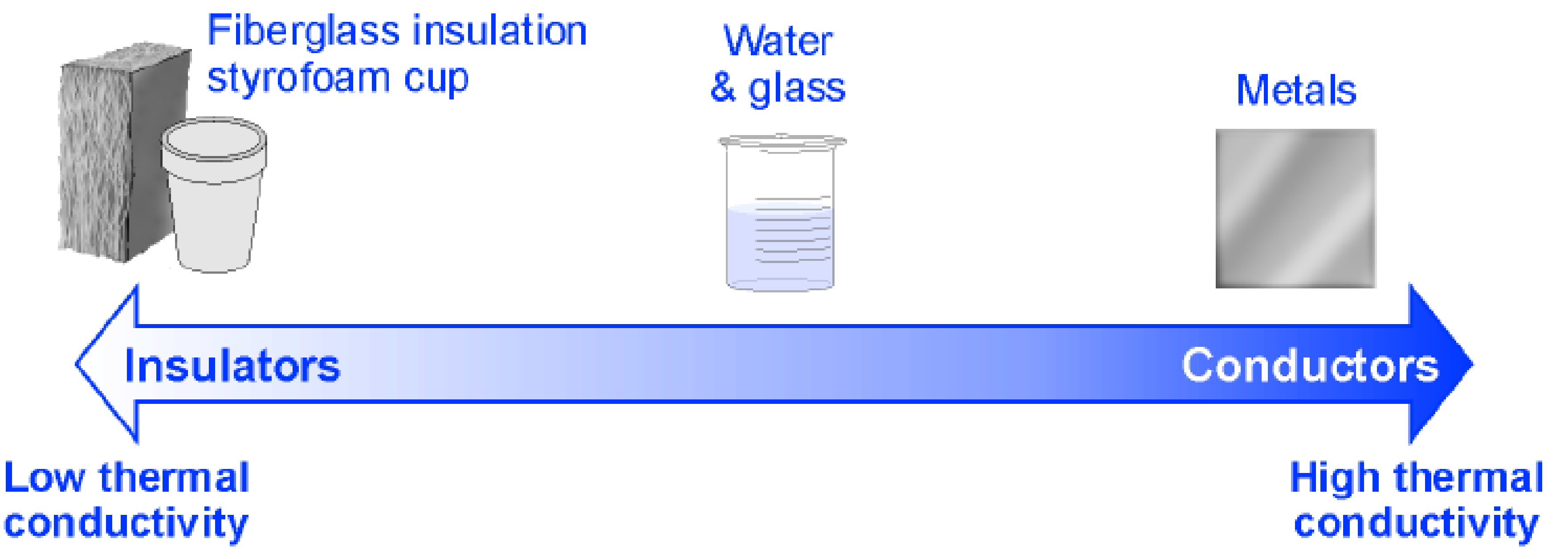
Conduction

Conduction is the transfer of heat by the direct contact of particles of matter. The molecules in the hot cup of liquid transfer their heat energy to the molecules in the cold spoon.



Thermal Conductivity

- The thermal conductivity of a material describes how well the material conducts heat.



Heat Conduction Equation

Thermal conductivity (watts/m°C)

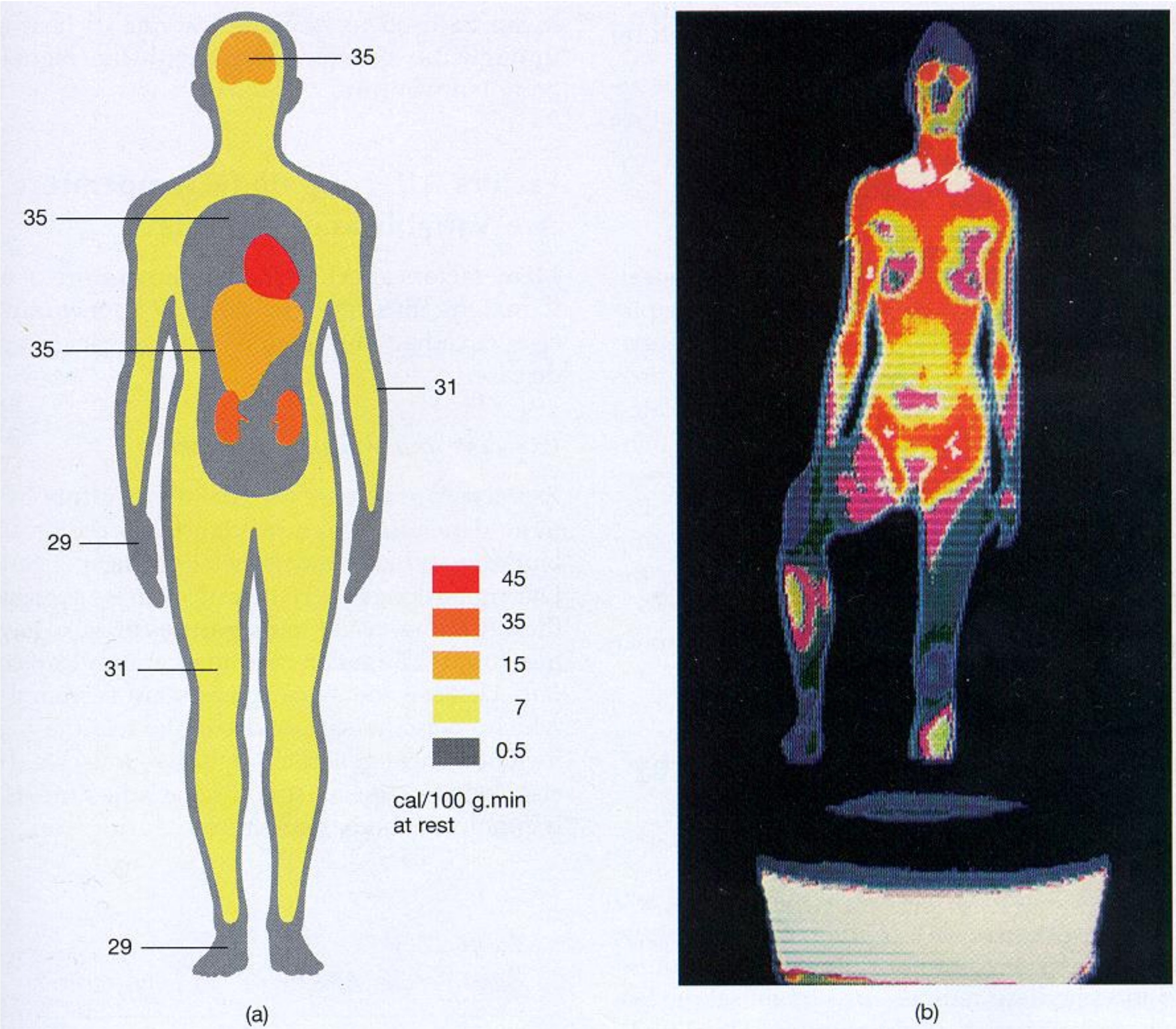
Area of cross section (m^2)

Heat flow (watts) →

$$P_H = \kappa \frac{A}{L} (T_2 - T_1)$$

Temperature difference (°C)

Length (m)



(a) (b)

The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form shown below where c is the specific heat. The relationship does not apply if a phase change is encountered, because the heat added or removed during a phase change does not change the temperature.

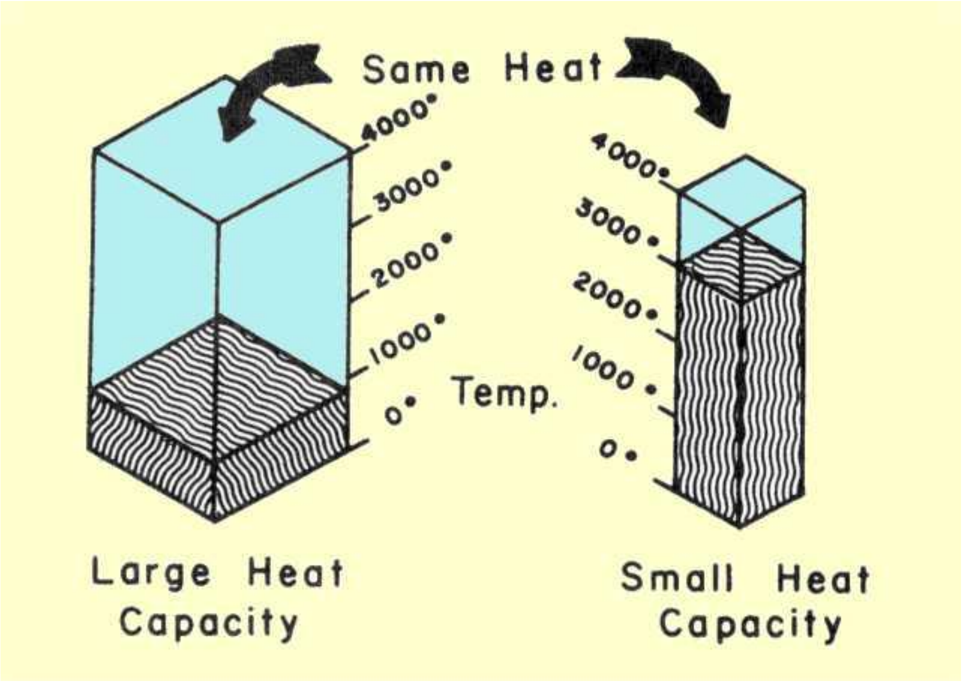
$$Q = cm\Delta T$$

heat added — specific heat — mass — change in temperature

The specific heat of water is 1 calorie/gram °C = 4.186 joule/gram °C which is higher than any other common substance. As a result, water plays a very important role in temperature regulation.

Heat capacity (usually denoted by a capital *C*, often with subscripts) is the measurable physical quantity that characterizes the amount of heat required to change a body's temperature by a given amount. In the International System of Units, heat capacity is expressed in units of joules per kelvin

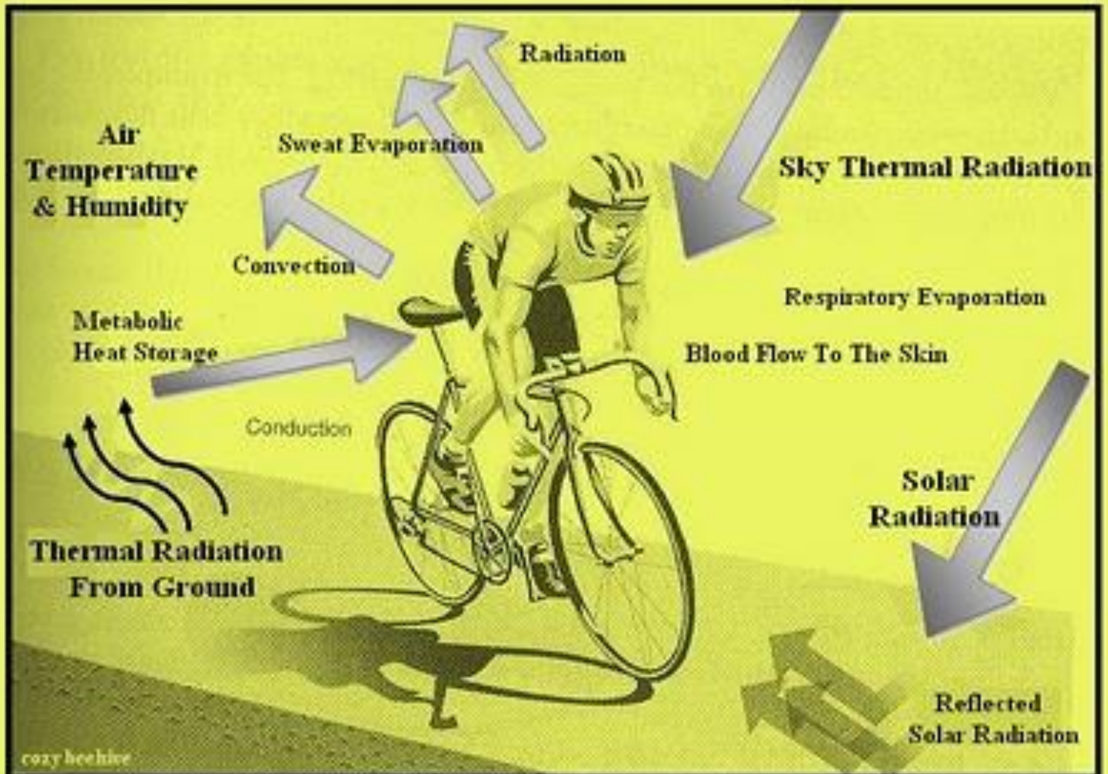
$$C = \frac{\Delta Q}{\Delta T}$$



Specific Heat Capacity
- c_p - *(J/kg^{o}C)*

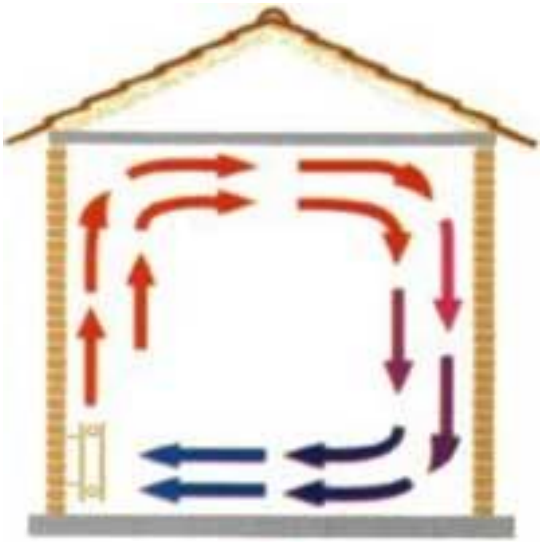
Human Body (average)	3470 J/kg°C

0,83 kcal/kg* ºC



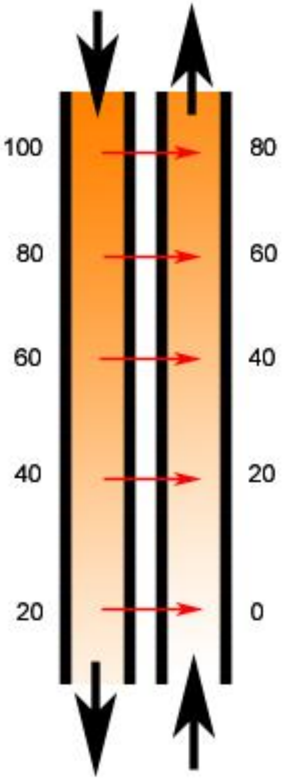
Modes Of Loss of Heat & Non Metabolic Gain of Energy

Heat Convection



Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it. Convection above a hot surface occurs because hot air expands, becomes less dense, and rises (see Ideal Gas Law). Hot water is likewise less dense than cold water and rises, causing convection currents which transport energy.

Counter-current heat exchange



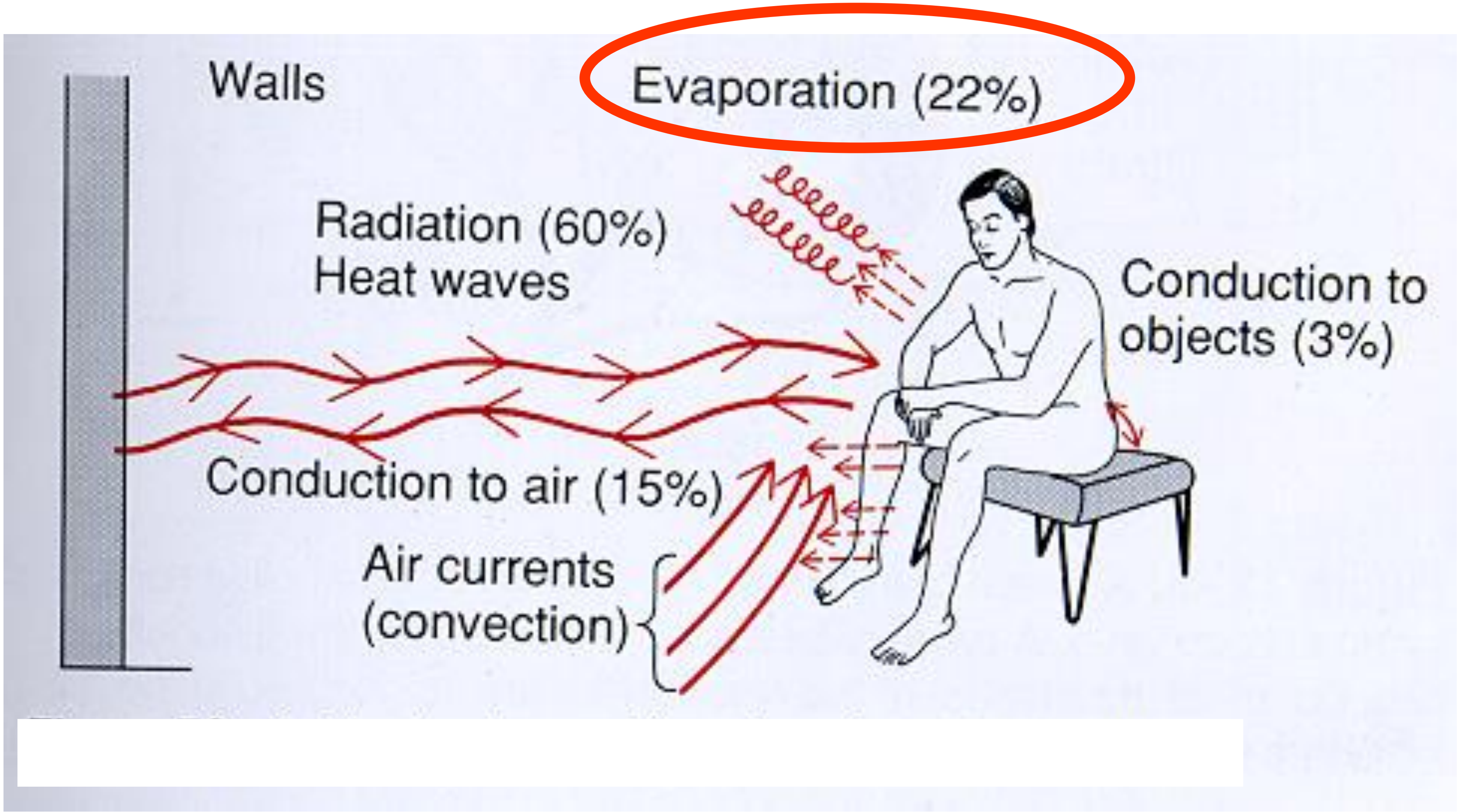
Heat conservation in the human body:
Limb arteries and venes run paralel

Wind chill (often popularly called the **wind chill factor**) is the felt air temperature on exposed skin due to wind. It measures the effect of wind on air temperature. The wind chill temperature is usually lower than the air temperature, since the air temperature is usually lower than the human body temperature.

The rate of heat loss by a surface depends on the wind speed above that surface: the faster the wind speed, the more readily the surface cools.

Unidirectional heat loss: Evaporation

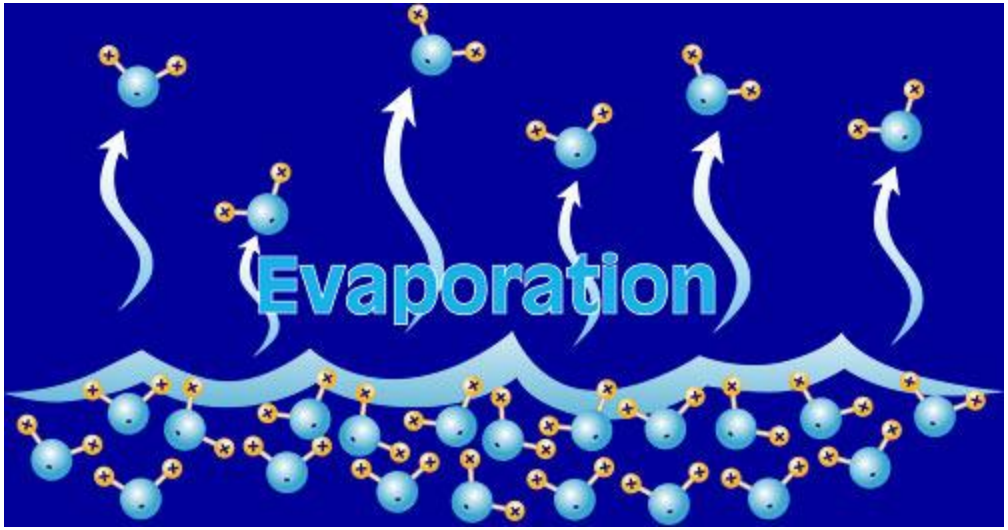
Sweat is produced from plasma water thus evaporative heat loss is also dependent on cutaneous blood flow!



Evaporation

Adding heat to water causes molecules to become increasingly energized and they start moving more rapidly, resulting in increase in distance between the liquid molecules and weakening of the forces between them.

At high temperature, therefore, more of the molecules near the water surface will tend to fly off into lower layers of the overlying air. At the same time, water vapor molecules in the lower air layers are also in continuous motion and some of them penetrate into underlying mass of water. Rate of evaporation at any given time depends on number of molecules leaving the water surface minus the number of molecules returning to water surface due to condensation.



The cooling effect of perspiration evaporation makes use of the very large heat of vaporization of water. This heat of vaporization is 540 cal/g at the boiling point, but is even larger, 580 cal/g, at the normal skin temperature.

How much energy is required to evaporate 600 ml water a day ?
1 ml water = 1 g

Q= 600 g x 580 cal/g = 348 000 cal=348kcal= 1457 kJ (a day)

P=Q/t= 1457 kJ/24x3600s ~ 17 watts

Limitation of heat loss

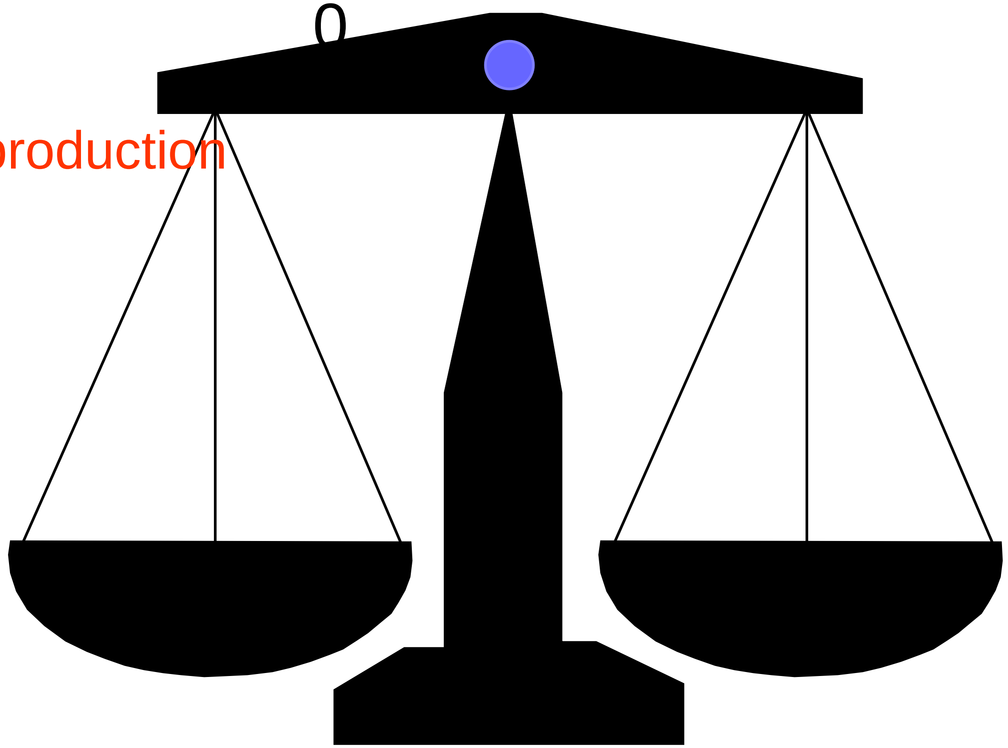
Humidity:

Relative humidity is a term used to describe the amount of water vapor that exists in a gaseous mixture of air and water vapor. Relative humidity represents a percentage of the maximum amount of humidity that can remain in the air, at the given temperature of the air.

The **heat index** (**HI**) is an index that combines air temperature and relative humidity in an attempt to determine the human-perceived equivalent temperature — how hot it feels, termed the felt air temperature . The human body normally cools itself by perspiration , or sweating , which evaporats and carries heat away from the body. However, when the relative humidity is high, the evaporation rate is reduced, so heat is removed from the body at a lower rate causing it to retain more heat than it would in dry air.

Constant body temperature requires heat balance

Heat storage= 0



- Metabolic heat production
- Radiation*
- Conduction*
- Convection*

- Radiation*
- Conduction*
- Convection*
- Evaporation

Heat gain

Heat loss

*These mechanisms are bidirectional and can be called collectively as heat exchange mec