

We now apply the ideas of Chapters 1-7 to the topic of THERMODYNAMICS. Thermodynamics is all about energy, and now we will have to worry about a new kind of energy, the INTERNAL ENERGY of a material, which increases as the material gets hotter, and which also changes if the material freezes or melts (you will get a formal DEF of internal energy soon). Our most important conclusions will come in Chapter 15 -- amazingly, by considering an imaginary system consisting of an ideal gas in an insulated pot with a piston-like lid, we will be able to figure out the maximum possible efficiency of any engine! We will get to that result in four lectures; but we need to start with some simpler ideas about TEMPERATURE and THERMAL EXPANSION.

TEMPERATURE is measured with a THERMOMETER; we usually imagine a long piece of glass with a tiny cylindrical cavity running down the middle and with a bulb of mercury (Hg) at the bottom of the cavity. The Hg expands linearly as it is heated (i.e. if you double the change in temperature, you double the expansion) so that the Hg level in the tube can be used to measure the temperature. To invent a TEMPERATURE SCALE, do the following experiment. Put the thermometer in boiling water and scratch a mark on the glass to indicate the resulting Hg level; then put the thermometer in contact with ice and scratch another mark on the glass to indicate the new (and now lower) Hg level. Now decide how many units, or degrees, you would like to have between these two levels and make the required number of scratches, spaced uniformly, in between your two original marks. Finally, pick a number for the temperature at the ice point. Here are three commonly-used scales which were invented in this manner:

	Fahrenheit (°F)	Celsius (°C)	Kelvin (K)
steam point (at P= 1 atm)	212	100	373.15
	} 180	} 100	} 100
ice point	32	0	273.15
absolute zero	-459.67	-273.15	0

As you can see from the figure, a temperature change of 180 °F is equivalent to a temperature change of 100 °C, i.e. $\Delta T_F = (\frac{9}{5} \frac{^\circ F}{^\circ C}) \Delta T_C$. On the other hand, the Celsius and Kelvin scales both have 100 units between the ice and steam points, so that $\Delta T_K = (\frac{1}{1} \frac{K}{^\circ C}) \Delta T_C$. Note that the Kelvin scale does not use the term "degree" to describe its unit; we would say, "the steam point is 100 Kelvin (K) above the ice point". To convert a given temperature T from one scale to another, you must first find $\Delta T = T - T_{ice}$, then convert the ΔT to the desired units or degrees of the new scale, and finally add your converted ΔT to the ice point in your new scale. Following this procedure leads to the following two equations for Celsius to Fahrenheit conversions and Celsius to Kelvin conversions. These two equations will appear on your equation sheet.

$$\text{Celsius to Fahrenheit} \quad T_F = (\frac{9}{5} \frac{^\circ F}{^\circ C}) T_C + 32 \text{ } ^\circ F$$

$$\text{Celsius to Kelvin} \quad T_K = (\frac{1}{1} \frac{K}{^\circ C}) T_C + 273.15 K$$

Scientists typically use either the Celsius or Kelvin scales. The particular advantage of the Kelvin scale is that the lowest possible temperature of a material (when the internal energy of that material is a minimum) is zero on that scale. In lecture, I will explain the CONSTANT-VOLUME GAS THERMOMETER, which can be used to determine absolute zero relative to the ice point.

The topic of THERMAL EXPANSION deals with the fact that materials expand when heated and contract when cooled. The basic idea for thermal expansion is similar to the basic idea for stress and strain:

$$\text{the cause of a change in shape} \propto \text{the relative change in shape}$$

Let's do a side-by-side comparison of ELASTICITY (a review) and THERMAL EXPANSION, in order to see how the above idea is applied in each case; for both cases, we start out with the idea that "the cause of a change in shape is proportional to the relative change in shape".

ELASTICITY

stress \propto strain \Downarrow

for the general case

$$\frac{F}{A} = (\text{modulus}) \left(\frac{\text{change in size}}{\text{original size}} \right)$$

 \Downarrow

for the 1D case

$$\frac{F}{A} = Y \left(\frac{\Delta L}{L_0} \right)$$

THERMAL EXPANSION

(change in T) \propto strain \Downarrow

for the general case

$$\left(\frac{\text{expansion}}{\text{coefficient}} \right) \Delta T = \frac{\text{change in size}}{\text{original size}}$$

 \Downarrow

for the 1D case

$$\alpha \Delta T = \frac{\Delta L}{L_0}$$

Note that the proportionality constant is on the right side for the elasticity case, but on the left side for the thermal expansion case. This is an accident of history; one could easily argue that it should be on the left in both cases, since the left sides are the CAUSES of the strain on the right sides. The 1D equation for thermal expansion is the DEF of the proportionality constant α :

DEF The COEFFICIENT OF LINEAR THERMAL EXPANSION (α) of a given material is

$$\alpha \equiv \frac{\text{strain}}{\Delta T} \quad \text{units are } ^\circ\text{C}^{-1} \text{ or } \text{K}^{-1}$$

where the strain appearing in the numerator is due to a 1D deformation produced by the ΔT appearing in the denominator.

We can similarly define a coefficient for 3D (volumetric) expansion:

DEF The COEFFICIENT OF VOLUMETRIC THERMAL EXPANSION (β) of a given material is

$$\beta \equiv \frac{\text{strain}}{\Delta T} \quad \text{units are } ^\circ\text{C}^{-1} \text{ or } \text{K}^{-1}$$

where the strain appearing in the numerator is due to a 3D deformation produced by the ΔT appearing in the denominator.

In these two DEFs, we do not need to worry about absolute values -- an increase in T always results in an increase in length or volume (and vice versa), so the signs will take care of themselves. Both α and β are positive-only scalars.

Since liquids flow, and thus take the shape of their container, α has no real meaning for liquids; liquids always undergo a volumetric expansion when heated. For solids, both α and β are meaningful, and β always turns out to be three times as large as α . The truth of this statement depends on the fact that the strains are always considered to be small; here is a little proof in 2D that will help you understand why $\beta = 3\alpha$.

Consider a rectangular area of width w and length ℓ , and thus with area $A = w \cdot \ell$. After heating to increase the temperature by ΔT , the new larger area may be written as $A + \Delta A$ or as $(w + \Delta w) \cdot (\ell + \Delta \ell)$. Now we just do a little algebra; if we get a $\Delta w \cdot \Delta \ell$, we will throw it away, because to three significant figures it won't make any difference (remember Δw and $\Delta \ell$ are assumed to be small compared to w and ℓ). Here goes:

$$\begin{aligned} A + \Delta A &= (w + \Delta w) \cdot (\ell + \Delta \ell) \\ &= w\ell + (\Delta w)\ell + w(\Delta \ell) + (\Delta w)(\Delta \ell) \Leftarrow \text{VERY small} \end{aligned}$$

$$A \text{ and } w\ell \text{ cancel} \Rightarrow \Delta A = (\Delta w)\ell + w(\Delta \ell)$$

$$\div \text{ by } (A = w\ell) \quad \frac{\Delta A}{A} = \frac{(\Delta w)\ell}{w\ell} + \frac{w(\Delta \ell)}{w\ell}$$

$$\text{DEF } \alpha \equiv \left(\frac{\Delta L}{L_0}\right) / \Delta T \quad = \alpha \Delta T + \alpha \Delta T$$

$$\Rightarrow \frac{\Delta A}{A} = 2\alpha \Delta T$$

Now, we didn't define an expansion coefficient for 2D, but you should be able to see that this result fits the pattern of our definitions -- the expansion coefficient in 2D would be 2α . Similarly, if we worked out β in the same way, we would get 3α (after a lot more algebra).

Different materials expand at different rates. I will demonstrate this

property during lecture with a DEMO called the BIMETALLIC STRIP. You will find a table of thermal expansion coefficients on page 342 of our text.

Next let's compare a strain created by thermal expansion with a strain created by stress for a commonly used construction material, steel. Let's look at the 1D case. Young's modulus for steel comes from the table on page 283; the coefficient of linear thermal expansion comes from the table on page 342.

ELASTICITY

$$\begin{aligned} \frac{\Delta L}{L_0} &= \left(\frac{1}{Y}\right)\left(\frac{F}{A}\right) \\ &= \left(\frac{1}{2.0 \times 10^{11} \text{ N/m}^2}\right)\left(\frac{F}{A}\right) \\ &= (5.0 \times 10^{-12} \text{ m}^2/\text{N})\left(\frac{F}{A}\right) \end{aligned}$$

THERMAL EXPANSION

$$\begin{aligned} \frac{\Delta L}{L_0} &= \alpha \Delta T \\ &= (12 \times 10^{-6} \text{ }^\circ\text{C}^{-1}) \Delta T \\ &= (12 \times 10^{-6} \text{ }^\circ\text{C}^{-1}) \Delta T \end{aligned}$$

A 1.0 °C change in T causes a strain which is about a MILLION times bigger than the strain caused by a stress of 1.0 N/m²! In other words, it takes a huge stress to give the same relative change in shape as caused by a small ΔT . To say the same thing one last way, you CANNOT EXPECT TO STOP THERMAL EXPANSION BY FORCE. You must design for thermal expansion in your selection of materials, taking into account that different materials expand at different rates. This is true whether you are designing a building or a surgical implant.

We will complete the topic of THERMAL EXPANSION in lecture by demonstrating that thermal expansion is "like a photographic enlargement" (i.e. holes get bigger not smaller), doing an example calculation, and discussing the special case of water near the freezing point. Then, we will move on to the topic of HEAT and INTERNAL ENERGY. Learn the following DEFs:

DEF The INTERNAL ENERGY (U) of a system of particles is the total energy of the system *except* the macroscopic KE (i.e. the translational KE plus the rotational KE) and the potential energy due to external interactions (such as PE_G with the Earth and/or PE_S with an external spring).

So U DOES NOT include most of the energies that we have learned about so far; of the energies we have discussed, only THERMAL ENERGY is included in the internal energy of a system of particles. You will learn what other types of energies are included soon. The word "heat" is reserved for a transfer of energy; here is the formal definition:

DEF HEAT (Q) is a flow of energy between two systems of particles due to a temperature difference between them. Q is a signed scalar in units of Joules.

Heat flow occurs when two objects of different temperatures are in contact. The flow of heat is always from the hotter object to the colder object; the internal energy of the hotter object decreases, while the internal energy of the colder object increases -- no energy disappears. The heat flow continues until the two object are at the same temperature. If we know from what material an object is made, then the resulting change in the temperature of the object due to an inflow or outflow of heat can be calculated using the following DEF:

DEF The SPECIFIC HEAT CAPACITY (c) for a given material of mass m is given by

$$c \equiv \frac{Q}{m\Delta T} \quad \text{units are } \frac{\text{J}}{\text{kg} \cdot \text{K}} \text{ or } \frac{\text{J}}{\text{kg} \cdot (^\circ\text{C})}$$

where Q is the necessary heat inflow (outflow) to create an increase (decrease) in temperature ΔT . Specific heat is a positive-only scalar.

This last DEF tells us the sign of Q ; since c is positive-only, heat inflow (creating a positive ΔT) must be positive and heat outflow (creating a negative ΔT) must be negative. You will find a table of specific heat capacities on page 350 of our text. Knowing c for various materials allows us to do many problems with CofE involving temperature changes.

After lecture, I suggest that you try Questions 1-7 in SAT 12.1.