

# Thermal and Statistical Physics

Frederik Denef

Transcribed by Ron Wu

This is an advanced undergraduate course. Offered in Fall 2014 at Columbia University. Required Course textbook: Schroeder, *Introduction to Thermal Physics*.

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# 1 Fundamental

There are two kinds of physical laws: primary laws like EM, QM, relativistic QM, QCD; and secondary laws like thermal dynamics. Secondary laws often have average characters, but they are too rigorous and provide accurate predictions. One big difference between primary and secondary law is that primary law allows time reversal, while for secondary law probability of time reversal is very low.

There are two tales of thermal physics (low energy, long distance, effective theory): macroscopic and microscopic. Macroscopic theory, called thermodynamics, study energy, work, entropy, specific heat, compressibility, equation of state, etc. Microscopic theory, called statistical mechanics or more accurately statistical quantum mechanics, developed a bit later, around 1900s, study microscopic models to predict macroscopic behaviors. The basic philosophy is that everything is random except conservation law.

One can find what we learn in this course applicable later for more advanced area of study, e.g. in condensed matter, in particle physics study fluid of particles.

## 1.1 Temperature and Equilibrium

We need a definition for temperature, but we won't get to a correct one any time soon, because it is not easy. One may think

$$T = \text{energy}$$

not right, for energy is additive, but  $T$  is not. Try

$$T = \text{energy/vol}$$

not right, say iron in the room has same temperature as other objects, but iron has higher energy, because it is more dense. Try

$$T = \text{energy/particle}$$

not right. E.g. Argon molecules in the air have lower energy than other substances, because they have less degrees of freedom.

Because we study system of lots of particles in assembling, we want to find the state of system, the average value, which should represent most of the particles in the assemble, that is we want particles come to equilibrium, meaning no further change when two initial different states brought together after a relaxation time. The relaxation time is normally on the order of picoseconds.

Types of equilibrium:

mechanical: e.g two gases with volume  $V_1$  and  $V_2$  put in a box separated by a movable piston. In the process coming to equilibrium, gases exchanges volumes till force balanced out, i.e.  $P_1 = P_2$  pressures become the same.

Thermal: e.g. two gases with energy  $U_1$  and  $U_2$  put in a box separated by a thermal conductive wall. They come to equilibrium by exchanging energies, till  $T_1 = T_2$

Diffusive: e.g. two gases with numbers of particles  $N_1$  and  $N_2$  put in a box separated by a penetrable wall. They come to equilibrium by exchanging particles, till  $\mu_1 = \mu_2$  chemical potentials become the same.

After system comes to equilibrium, we can measure temperature by thermometers, which give a non-analytic operational definition of temperature. If we define some scale, Celsius, roughly  $0^{\circ}C$  freezing water,  $100^{\circ}C$  boiling water.

Most thermometers belong to one of the two types: thermal expansion and electrical conductivity. Thermal expansion is easy to explain. For normal material, it expenses in equal interpolation scheme, i.e.  $\Delta l \propto \Delta T$ . More amazingly, if we use dilute gas (model for ideal gas), fix volume, measure pressure, i.e. pressure is a function of temperature  $P = P(T)$ . The relation is linear, and if nothing complicated happens, as temperature goes down further more, pressure will go down to close to 0. This gives sense of absolutely 0 temperature. One then find the conversion between Kelvin and Celsius

$$T_{\text{Kelvin}} = T_{\text{Celsius}} + 273.15$$

## 1.2 Ideal Gas

Take some highly diluted gas, we find ideal gas law

$$PV = nRT$$

$n$  moles,

$$R = 8.31 J/mol \cdot K$$

gas constant. Or write

$$PV = NkT$$

$N = N_A n$ ,  $N_A = 6.022 \times 10^{23}$  Avogadro number, defined by number of atoms in 12g of the carbon-12.

$$k = \frac{R}{N_A} = 1.381 \times 10^{-23} J/K$$

Boltzmann constant. In room temperature  $kT = 0.026 eV = \frac{1}{40} eV$ , take  $T = 300 K$

Using ideal gas law, one can find the atmosphere pressure

$$P(z) = P(0)e^{-mgz/kT}$$

assuming same  $T$ , where  $m$  mass of air molecules.

Correction to ideal gas law

Virial expansion

$$PV = nRT[1 + B(T)\left(\frac{n}{V}\right) + C(T)\left(\frac{n}{V}\right)^2 + \dots]$$

The correction terms make up 1/1000 precession to the ideal gas law. Those terms would not be there if molecules had no sizes.

Another type of correction, Van der Waass

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nkT$$

This takes into account not only the finite sizes of molecules but also attraction from molecules.

## 1.3 Kinetic Model

Lecture 2

(9/4/14)

## **1.4 Equipartition**

## **1.5 Heat & Work**

## **1.6 Compression Work**

Lecture 3

(9/9/14)