Theoretical Physics IV

Thermodynamics
and
Statistical Physics

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Chapter 1

Introduction and overview

Up to now, during the course of theoretical physics the motion of a single particle (or, at best, a few particles) under the influence of external fields has been considered, first classically, then quantum mechanically. We had seen that, when relativistic motion and quantum mechanics are combined, the sheer concept of single-particle dynamics breaks down, because of the possibility of particle-antiparticle pair generation in an interacting system at sufficiently high energies. The relativistic quantum theory becomes necessarily a theory of many particles (i.e. a field theory). While in relativistic quantum theory the many-particle aspect came, at first glance, as a necessary, but "unwanted" accident, there are many systems in the world around us, which consist naturally of a huge number of Particles.
Examples are

- atoms or molecules in a gas, liquid or solid
- electrons in a metal
- magnetic moments in a ferromagnet
- atomic nuclei and electrons in a plasma (star)
- photons in a laser
- cars on a highway
- individuals in a biological population ...

It is seen that there is a vast variety of many-particle systems with various types of interactions between the particles. Characteristic for all many-particle systems is their huge number of degrees of freedom, typically $\approx 10^{23}$ (coordinates and momenta of each particle).

It is *neither possible nor desirable* to describe the dynamics of all microscopic degrees of freedom in a many-particle system. The latter holds for two important reasons:

1. Even knowledge of *all microscopic* degrees of freedom would not allow us easily to describe the *macroscopic* behavior of a system, which is observed in experiments and which is relevant for practical applications.

   Example:
   Knowing $(\vec{x}, \vec{p})$ for all atoms in a gas does not immediately tell us its temperature T and pressure P. Calculating T, P would be beyond any computer's memory.

2. Many-particle systems often show *collective behavior ordering phenomena, phase transitions* on the macroscopic level, which could not even principally be deduced from the microscopic coordinates.

   Examples:
   Superconductivity, magnetic and other phase transitions, collective modes (waves in water etc.), fractional quantum Hall effect: fractional excitation.

   Thus, the microscopic description breaks down on a more fundamental than merely computational level:

   > "The whole is more than the sum of its parts."

   On the macroscopic level fundamentally new complexity arises, which cannot be seen on the microscopic level.

It is the task of thermodynamics and statistics to develop methods for describing (complex) macroscopic systems consisting of many degrees of freedom. This proceeds in three major logical steps:

1. Identify and define relevant macroscopic variables to describe a system:
   state variables: T, P, V, N, E, S
2. Provide rules for the dependence of the state variables upon each other

thermodynamics

3. Develop methods to calculate the state variables and their mutual dependence from their microscopic Hamiltonian. → Statistical methods required, because of vast number of degrees of freedom.

statistical physics

Link between microscopics and macroscopic behavior.

Thermodynamics
has been developed during the second half of the 19th century and is a closed field of research now. It is a phenomenological theory where the state variables, like temperature T, entropy S etc., are defined in an implicit way through their relation to other variables. This often leaves the impression of thermodynamics being incomplete. However, it is the nature of a phenomenological theory, that only implicit definitions are possible. The mathematical structure of thermodynamics is that of the theory of analytical functions of multiple variables. The state variables are defined as derivatives of a given analytical function (potential) and are, thus, related to each other purely on mathematical grounds, not through physical interactions.
Thermodynamics has been the basis for the development of engines like the steam engine etc., which revolutionized industry in the 19th and early 20th century. One of its pioneers was Clausius who was the head of the Bonn physics institute.

Statistical physics
provides the microscopic basis and methods for the definitions and relations of thermodynamics. It thus allows to calculate macroscopic quantities from a microscopic approach, not only in relation to each other.
Statistical physics is now one of the big active fields of research and is applied to many different systems ranging from many-body quantum systems (superconductivity, laser . . .) to biological systems and populations and to the stock market.