Surrounded by physics

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Preface

This book is the result of a series of lectures I gave for a number of years to first year students in applied physics at Delft University of Technology. The idea for such a course started from discussions with our students. They uttered the general complaint, that the freshmen year of their studies was, to their taste, too much dominated by classes and courses in mathematics. Obviously, the response of the staff was that it is absolutely necessary to have a good understanding of mathematics, especially calculus and linear algebra, at an early as possible stage. Otherwise, it would be virtually impossible to bring the physics course to university level. The common language of all physicists and many other scientists and engineers is math. Nevertheless, the students made it clear that more physics in their first year curriculum would be very welcome.

It was decided to grant their wish and set up a course with as theme Physics of Daily Life. This idea was of course inspired by the series of books that Prof. Dr. M. Minnaert wrote in the 30s of the twentieth century. In the course, no specific topics like quantum mechanics or thermodynamics would be taught, but the aim was rather to stroll along all kinds of more or less familiar phenomena. By touching on these phenomena, different parts of physics and the accompanying theory would be discussed with the students. Being exposed to phenomena and open questions and being encouraged to think as a physicist was more important than providing the theoretical background along the traditional lines of the subdisciplines and theories of physics.

I was asked in the fall of 1999 by the director of education of Applied Physics, Prof. F. Tuinstra, whether I could prepare and give such a course. The idea was challenging and I agreed. But, I didnt want to lecture by story telling and picture viewing; it had to be a course in which we would do physics, beit at the level of a freshmen. Moreover, I didn't want to end with a written exam. In stead all students had to prepare an essay in which they discussed a topic they had chosen themselves from the physics of daily life in a broad sense. Moreover, they had to write a Physics Essay. The result would vary, but there were some amazing examples, showing that if challenged, young and bright people can achieve a lot. Finally, I think we all enjoyed the classes and the essays. Physics is a beautiful subject once you dive into it.

I would like to thank all my students, who came up with ideas and questions about physics in daily life. Furthermore, I would like to thank my colleague, Prof. Chris Kleijn, who was always willing to listen to my ideas and help sorting out what the

physical explanation was and how to convey that to freshmen students as best we can.
This book is dedicated to the memory of my loving father, who unfortunately did not live long enough to see the printed version.

'Who loves nature observes her the same way he/she breathes and lives: from a native inner drive'. This is the openings sentence of Prof. Dr. M. Minnaert's series of three books about the physics of our environment.
Minnaert (a Belgian physicist who died in 1970) published his books in 1937 for the first time. They have been translated in many languages and are still in press, showing that a basic understanding of the physics of the world around us is still popular. This can also be seen in the weekly science sections of the broadsheet newspapers: many of them have a column that deals with questions from its readers asking for an answer to some remarkable observation. In many cases the answer is found in the physics of every day life. Some of the questions are for a physicist rather obvious, others are not so easyly to answer. In many cases the observation seems trivial, but the answer can push you deeper and deeper into the world of physics. And as always, with an increasing level of understanding the phenomena in question gain in beauty. This book is written with the idea that the world around us is full of beauty and that appreciation of it is raised as the understanding in terms of physical reasoning is brought to a higher level. Furthermore, it is just fun to think about what we see, hear, feel and try and find an explanation.

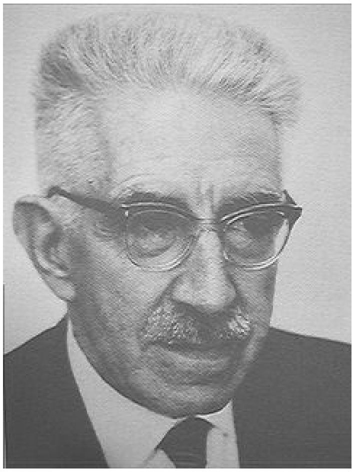

Figure 1 Minnaert (1893-1970).

Since Prof. Minnaert's book saw the light, many other books about the physics of daily life have been published. Some relatively superficial, others just for fun reading but also quite a few that try to give answers and insight based on sound physical reasoning.
This book tries to provide a level that is adequate for anyone with a basic knowledge of physics and an engineering degree. It is not aimed at the general public. Hence, equations have not been avoided, on the contrary, equations and derivations help physicists understanding what is going on. Moreover, they provide the possibility to quantify and make predictions. This allows scientists to further build up their knowledge about phenomena. I assume that the reader will have some basic knowledge of physics and is capable of following mathematical manipulation. However, I do understand that many potential readers will have had their educa-

tion years ago and will not memorize all the laws. So, I have tried to put these in as refreshment. Sometimes, this might be a little overdone. Never mind, the main text can still be followed and the idea behind the phenomena captured.

October 2008
Robert F. Mudde

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Chapter 1

Elephant ears, dolphin fins and the balance equation

1.1 Keeping the balance

It is easy to come up with a set of questions concerning daily life observations that require some degree of physics in answering. At first sight some may be only remotely connected to physics, like the question:

- *Why do (African) elephants have such enormous ears?*

Part of the answer can only be given if the balance between production of heat and the desired temperature of the animal is taken into consideration. All mammals have to maintain a body temperature of about 37°C. However, even in rest the animal will use energy which is partly converted into heat within its body. Obviously, to arrive at a steady state as far as its temperature is concerned, the animal will have to transport this heat to the environment as can be seen from a very elementary (steady state) heat balance:

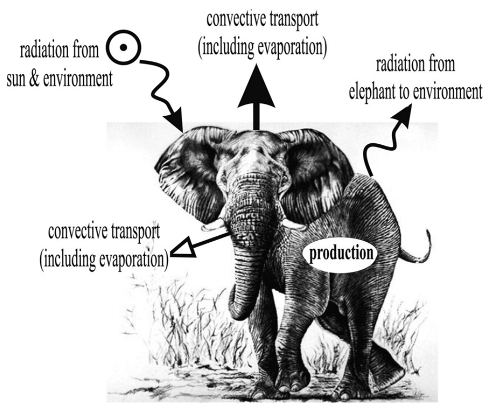

Figure 1.1 Heat production and flows from and to an elephant.

$$0 = \text{heat flow from environment - heat flow to environment} + \\ + \text{ internal heat production} \quad (1.1)$$

The heat production is proportional to the volume of the elephant.The heat flows are more complicated as there are various ways to transport heat from an object to its surroundings. Generally, we split these in three groups: heat transport by conduction, by convection and by radiation. The relative importance of these three depends on the particular circumstances. For instance, if the elephant is standing in the bright sunshine, it is obvious that he will receive radiation from the sun that will count as an inflow of heat. If there is wind, the elephant might be cooled by the wind if the air is colder than the outside of the elephant or heated if the air temperature is higher than its skin temperature.
Furthermore, for animals there is the very important possibility to loose heat due

to evaporation of water, i.e. by sweating. For all these flows of heat it holds that they are proportional to the surface of the elephant. So, if we look at the heat balance of the elephant, we see that the internal production of heat is proportional to the volume of the elephant and that the net balancing heat loss is to a good extend proportional to its surface. This gives us a good part of the explanation for the big ears: increase of (cooling) surface without increase of (heat producing) volume.

- *How does a dolphin in cold sea water prevent itself from too much heat losses via its flippers?*

This question can be investigated along the same lines as in the above example. Now we focus on the flippers. It will be clear that the blood that flows through them will be cooled substantially, being 'surrounded' by cold sea water. Nature has found a clever way of dealing with this, that humans (especially engineers) since the industrial revolution started to utilize frequently: the heat exchanger. In the flippers of the dolphin the veins carrying blood that flows from the body into the flippers are clearly twisted around the return veins that carry the blood back into the body (see Figure 1.2).

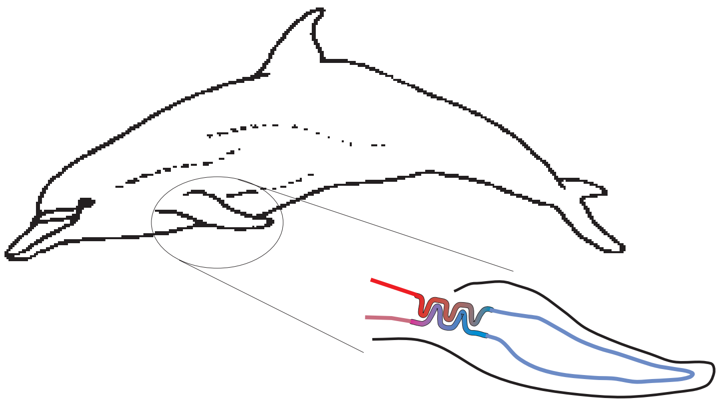

Figure 1.2 Schematic representation of the veins in the dolphin flippers.

What happens is that the warm blood coming from the dolphin body exchanges heat with the blood that returns to the body. The latter is obviously cooled by the cold surrounding sea. The driving force for the heat flow from the hot to the cold flow is the temperature difference between the two blood streams.

Intermezzo: balance equations

Figure 1.3 Changing number of people in a country due to in, out flow and birth and death.

In physics 'conserved quantities' form a special type. They are at the foundation of physical theories for the obvious reason that no matter what happens during an event a conserved quantity will come out the same as it went in. This does not mean that nothing is changing: the conserved quantity can be redistributed over the various parts participating in the event. In physics, mass, momentum and energy are amongst the most important conserved quantities. It is, however, in many cases more convenient to think of these quantities in terms of a balance rather than a conservation equation. The latter expresses that the quantity can not disappear. the former leaves room for 'production' of a quantity under consideration (where a negative production stands for destruction). An easy example, although not from physics, is the number of people in a country. Obviously, 'people' is not a conserved quantity: the total number of people varies over time, as there is birth and death. If these two were absent, then of course the total number of people would be conserved. For the country chosen, the number of people present at time $t+\Delta t$, let's call that $N(t+\Delta t)$ depends on the number at time t, $N(t)$ and on the number of people coming into the country during the time interval Δt, the number going out during Δt as well as the number of people that died and are born in this period. We group the latter two together into a net production, *Prod*. We can write this now in a balance equation:

$$N(t+\Delta t) - N(t) = in(\Delta t) - out(\Delta t) + Prod(\Delta t) \tag{1.2}$$

The terms '*in*' and '*out*' can be written more convenient as a mean flow in or out of the country (in number of people per second) acting during the time interval Δt. Note that this flow in and out requires actual crossing of the border of the country by the people. Similarly, we will write the production term as the number of people born in the country minus those who die in the country both per unit of time, multiplied by the time interval. Using these we can write the above equation as:

$$N(t+\Delta t) - N(t) = flow_{in} \cdot \Delta t - flow_{out} \cdot \Delta t + P \cdot \Delta t \tag{1.3}$$

By dividing both sides by Δt and taking the limit $\Delta t \to 0$, we arrive at the basic form of a balance equation, which describes the dynamics of the quantity under consideration, in the above example the number of people in the country.

$$\frac{dN}{dt} = flow_{in} - flow_{out} + P \tag{1.4}$$

In case of a steady state, obviously, the rate of change with time is zero and we get:

$$\text{st.st.} \quad \to \quad 0 = flow_{in} - flow_{out} + P \tag{1.5}$$

Hence, this is a passive system that does not cost the dolphin any extra energy and furthermore is sensitive to the heat loss of the blood by its nature. The colder the returning blood the more heat is transferred from the hot blood to the cold. Consequently, the colder the hot blood becomes before being 'exposed' to the cold sea. In this way the system is self regulating and the temperature of the blood entering the dolphin's body is as high as possible without the input of extra energy by the animal.

In many technical applications heat exchangers (or mass exchangers for that matter) can be found that use a similar arrangement.

Chapter 2

The sky has a limit

2.1 Thickness of the atmosphere

The earth is a special planet. It has the right conditions to make life possible. It has water in enormous quantities and is blessed with an atmosphere containing oxygen and other gases. It has the right distance from its star, our sun, to allow for a temperature that leaves water liquid.

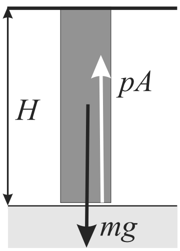

Figure 2.1 The pressure 'carrying' the atmosphere.

The earth radius is about 6378 km. The atmosphere forms only a thin layer around the earth. How thick is this layer? Let's make a guess. We do know that the pressure at the earth surface is 1 atm. Just like in water, this pressure can be explained as hydrostatic pressure: the total weight of the atmosphere is 'lifted' by the pressure. So, a first rough guess could be: assume the density of the air is constant (1.2 kg/m^3). Then, a simple force balance over a vertical column with cross-sectional area A of the atmosphere gives:

hydrostatic pressure

$$p * A - F_{grav} = 0 \Longrightarrow p * A - \rho A H g = 0 \Longrightarrow H = \frac{p}{\rho g} = 8.6\,\text{km} \tag{2.1}$$

Intermezzo: force balancing

A force balance can be set up for any material entity that is either at rest or moves at a constant velocity. This notion goes back to Newton, who formulated this as one of his main physical laws: given a mass at rest or moving at a constant velocity, then the sum of forces acting on this mass must be zero. In vector notation we can write this as:

$$\sum_i \vec{F}_i = 0 \tag{2.2}$$

This equation is a vector relation. Hence, it holds for the different components of the vector, *e.g.* for the x, y or z direction in a Cartesian coordinate system.

Obviously, this answer must be wrong as air planes routinely cruise at a height of 10 km. Thus, we need to improve our model. And it goes without saying that the constant density is a very dubious assumption. Of course, going up in the atmosphere, the density decreases. We can use the ideal gas law to relate the density to the pressure. The latter is also decreasing with height as the pressure at height z does not have to carry what is below z. But the density is also a function of the temperature. Let's try isothermal conditions, hence we set $T = 0°C =$273 K.

Intermezzo: Ideal gas law

An ideal gas is a physical concept that describes the relation between the pressure, temperature and volume of a given number of moles of gas. Ideal gases do not really exist, but gases in which the molecular attraction between the molecules plays a negligible role are accurately described by it. Boyle and Gay-Lussac formulated the basic relations, that were later put together to form the ideal gas law:

$$pV = nRT \tag{2.3}$$

with p the pressure, V the volume occupied by the gas, n the number of moles of the gas and T the temperature. The constant R is the gas constant and has a value of 8.3144 J/molK.
Usually, dilute gases follow the ideal gas law. At temperatures well above the boiling point of nitrogen and oxygen, air can be treated as an ideal gas. By multiplying the above equation by the molar mass M, the ideal gas law describes the relation between pressure, temperature and density (ρ):

$$pV = nRT \rightarrow pM = \frac{nM}{V}RT = \rho RT \tag{2.4}$$

force balance: slice

Now we need to set up a force balance that takes into account the variation of the density with height. Therefore, consider a small slice out of a vertical column of the atmosphere, between z and $z+\Delta z$ (see Figure 2.2).

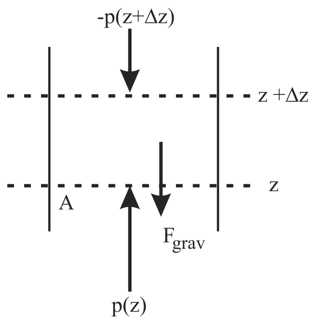

Figure 2.2 Forces on a small slice of the atmosphere.

The weight of this slice is: $\rho A \Delta z g$. Three forces act on this slice: at the bottom the pressure at that position pushes upwards: $p(z)A$; at the top the pressure pushed downwards: $p(z+\Delta z)A$ and, of course, gravity. Thus for a steady state we have according to Newton that the sum of the forces is zero:

$$p(z)A - p(z+\Delta z)A - \rho A \Delta z g = 0 \tag{2.5}$$

If we use a Taylor expansion on $p(z+\Delta z)$

$$p(z+\Delta z) = p(z) + \frac{dp}{dz}\Delta z + h.o.t. \tag{2.6}$$

we can simplify eq.(2.5) to

$$\frac{dp}{dz} = -\rho g \tag{2.7}$$

Intermezzo: Robert Boyle & Joseph Gay-Lussac

The ideal gas law is attached to the work of Robert Boyle (1627-1691) and Joseph Gay-Lussac (1778-1850). Boyle experimented with gases and reached an important conclusion, now known as Boyle's law: "For a gas under constant temperature, the volume is inversely proportional to pressure". In formula: $pV = const.$ at constant T. He stated that gases are made of tiny particles spaced very far apart. After improving Guericke's pump, he demonstrated that a feather and a lump of lead fall at the same speed in a vacuum.

Figure 2.3 Robert Boyle (1627-1691).

Figure 2.4 Joseph Gay-Lussac (1778-1850).

Joseph Louis Gay-Lussac extended the law of Boyle, by realising that all gases expand by equal amounts when subject to equal increments in temperature, if the pressure is kept constant: $V \propto T$ for constant p. By combining these two laws with the notion that gases are made of particles, the ideal law can be understood.

For isothermal conditions the density and pressure are linked according to: *isothermal atmosphere*

$$pV = nRT \rightarrow p = \rho \frac{RT}{M} \tag{2.8}$$

with M the molar mass of air (= 28.8 $\cdot 10^{-3}$ kg/m^3). Combination of the last two equations gives:

$$\frac{1}{\rho}\frac{d\rho}{dz} = -\frac{gM}{RT} \tag{2.9}$$

Thus, for the density profile in the atmosphere (taking $z = 0 \rightarrow \rho = \rho_0$) is:

$$\frac{\rho(z)}{\rho_0} = exp\left(-\frac{gM}{RT}z\right) \tag{2.10}$$