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Introduction: Classical Physics and the Physics of Information Technology

This chapter…
describes the view of classical physics about matter. The knowledge developed from these concepts has led to the first industrial revolution; however, it is not sufficient to explain many of the present technologies. The need for a substantial extension of physics is demonstrated by following the development of lighting technology.

1.1 The Perception of Matter in Classical Physics: Particles and Waves

The task of physics is the description of the state and motion of matter in a mathematical form, which allows quantitative predictions based on known initial conditions. Mathematical relationships are established for simplified and idealized model systems. Classical physics considers two basic forms of matter: *bodies* and *radiation,* characterized by mass m and energy E, respectively. The special relativity theory of Einstein (see Section A.9) has established that these two forms of matter can be mutually transformed into each other. In nuclear fusion or fission, for example, part of the initial mass will be converted into electromagnetic (EM) radiation (in the full spectral range from heat to X-rays), while energetic EM radiation can produce electron–positron pairs. The equivalence of mass and energy is expressed by $E = mc^2$. Still, the models used for the two forms of matter are quite different.

In classical physics, radiation is a *wave* in the ideally elastic continuum of the infinite EM field. Waves are characterized by their (angular) frequency ω and wave number k. These quantities are not independent, and the so-called dispersion relation between them, $\omega = \omega(k)$, determines the phase velocity v_f and group velocity v_g of the wave (see Sections A.5 and A.6). The energy of the wave is $E \sim v_f|\boldsymbol{E}_0|^2$, where $\boldsymbol{E}_0$ is the amplitude of the EM wave.

In contrast to the continuous EM field, bodies consist of discrete *particles.* The fundamental building blocks are the elementary particles[1] listed in Table 1.1.

1 Solids, fluids, and gases all consist of atoms with a nucleus and electrons. The nucleus consists of protons and neutrons, both of which are made up of quarks.

Essential Quantum Mechanics for Electrical Engineers, First Edition. Peter Deák.

Table 1.1 The elementary particles.

Particles	First generation	Second generation	Third generation
Quarks	Up (u)	Charm (C)	Top (t)
	Down (d)	Strange (S)	Bottom (b)
Leptons	Electron (e)	Muon (μ)	Tau (τ)
	e-Neutrino	μ-Neutrino	τ-Neutrino

The model of classical physics for particles is the *point mass*: a geometrical point (with no extension in space) containing all the mass of the particle. It has been found that the center of mass of an extended body is moving in such a way as if all the mass was carried by it, and all the forces were acting on it. Therefore, the concept of the point mass can even be applied for extended bodies. The point mass can be characterized by its position in space ($\boldsymbol{r}$) and by its velocity ($\boldsymbol{v}$), both of which can be accurately determined as functions of time. These kinematic quantities are then used to define the dynamic quantities, *momentum* $\boldsymbol{p}$, *angular momentum* $\boldsymbol{L}$, and *kinetic energy* T (see Section A.3).

The laws and equations of classical physics are formulated for point-mass-like particles and for waves in an infinite medium.

1.2 Axioms of Classical Physics

The motion of interacting point masses can be described by the help of the four Newtonian axioms (see Section A.2), which allow the writing down of an equation of motion for each point mass. Unfortunately, this system of equations can only be solved if the number of point masses is small or if we can assume that the distance between them is constant (rigid bodies). If the number of particles is high and the interaction between them is weak, a model of noninteracting particles (ideal gas) can be applied, and the system can be described by thermodynamic state variables. The changes in these are governed by the four laws of thermodynamics and by the equation of state. Actually, the state variables can be expressed by the Newtonian dynamic quantities, and the equation of state, as well as the four laws, can be derived from the Newtonian axioms with the help of the statistical physics and the kinetic gas theory (Figure 1.1).

The behavior of the EM field is described by the four axioms of Maxwell's field theory (see Section A.6). Far away from charges, these give rise to a wave equation, the solutions of which are the EM waves, traveling with the speed of light. The propagation of a local change in the field strength $\boldsymbol{E}$ can be given by the wave function $\boldsymbol{E}(\boldsymbol{r},t)$. The wave front is defined by the neighboring points in space where $\boldsymbol{E}$ has the same phase. Each point of the wave front is the source of a secondary elementary wave, and the superposition of the latter explains the well-known wave effects of refraction and diffraction.

Elastic and plastic (deformable) bodies (solids and fluids) contain a huge number of interacting particles, and neither the model of rigid bodies nor the model of

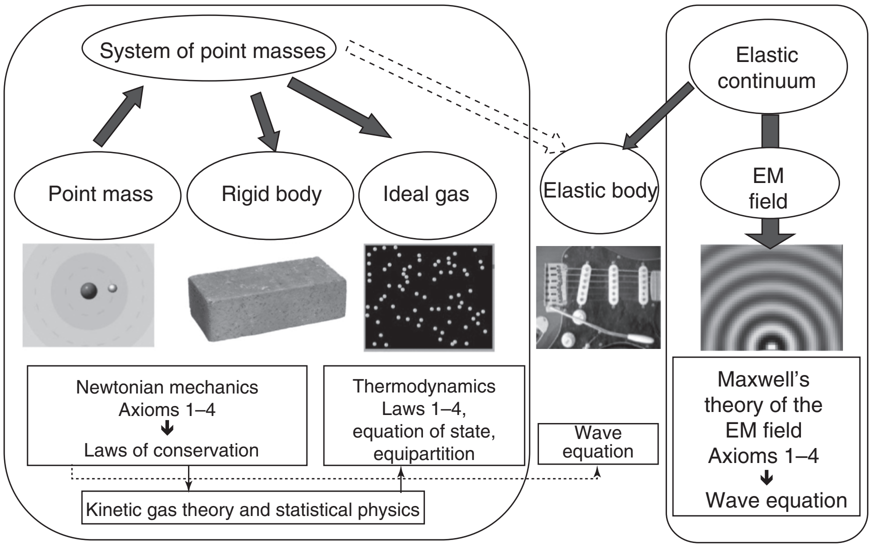

Figure 1.1 Models and axioms of classical physics.

the ideal gas can be applied. Instead, a continuum model can be used by assuming a continuous mass distribution, neglecting the corpuscular nature of the body. In the case of elastic bodies, the Newtonian equation for an infinitesimal volume of the continuum leads to a wave equation. The solutions are mechanical waves, corresponding to the propagation of local changes in the position (vibrations). The concepts and mathematics of mechanical and EM waves are quite similar.

1.3 Status and Effect of Classical Physics by the End of the Nineteenth Century

As we have seen in the previous subsection, classical physics contains two relatively independent parts: *mechanics* (from which also the thermodynamics can be derived) and *electrodynamics* (including optics).[2] Particles in classical mechanics are described by the concept of the point mass. In a conservative force field, where the potential energy $V(x,t)$ can be defined, the position of the point mass can be obtained from the Newtonian equation of motion:

$$m\ddot{x}(t) = \frac{dV(x,t)}{dx} \tag{1.1}$$

Historically (see Figure 1.2), the concept of the point mass has evolved, among others, from

2 More generally, one should talk about field theory. However, as we explain later, the only really relevant force field in electrical engineering is the EM field.

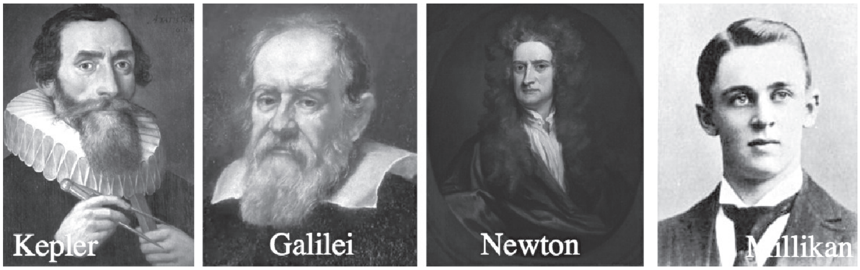

Figure 1.2 Scientists who were instrumental in the development of the point mass concept for particles. The pictures are taken from the public domain image collection of http://de.wikipedia.org

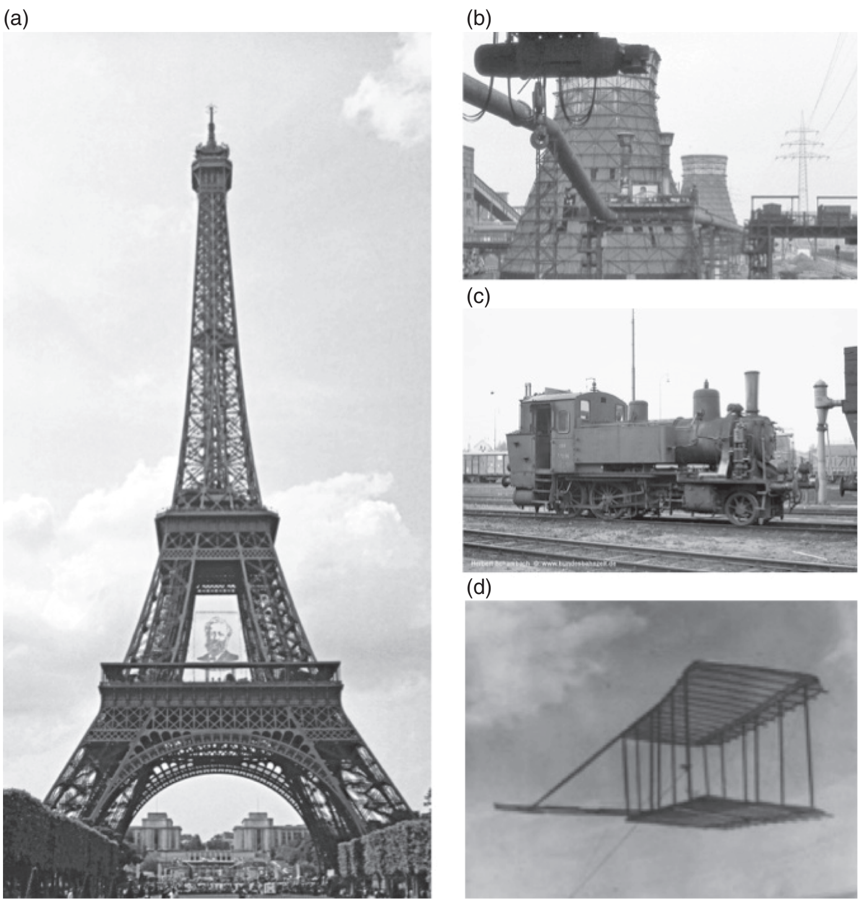

Figure 1.3 Application of mechanics and thermodynamics around the end of the nineteenth century. (a: The picture of the Eiffel tower was taken by the author. b: Power station, reproduced with permission of Daniel Hinze. c: Old locomotive, reproduced with permission of Herbert Schambach. d: The picture of the airplane was taken from the public domain of http://en.wikipedia.org.)

- the mathematical formulation of the observed regularities in the planetary motions (by, e.g., *J. Kepler*);
- the mathematical formulation of the experimentally observed motion of bodies on earth (by, e.g., *G. Gallilei*);
- the establishment of the axioms of mechanics (by *I. Newton*).

The concept of elementary particles, as the building blocks of a body, could later be confirmed in electrical measurements, too (e.g., by *E. Millikan,* who has shown that the electric charge of an oil droplet, floating in the field of a capacitor, can only be changed by discrete amounts, corresponding to the elementary charge, i.e., to the charge of an electron). The application of the principles of mechanics and thermodynamics around the end of the nineteenth century has led to the invention and optimization of structures and machines such as the ones shown in Figure 1.3.

The interpretation of light as a wave in the EM field is based on the wave equation, derived from Maxwell's axioms:

$$\frac{\partial^2 \psi(\mathbf{r}, t)}{\partial t^2} = v_f^2 \frac{\partial^2 \psi(\mathbf{r}, t)}{\partial \mathbf{r}^2} \tag{1.2}$$

where ψ is either the electric or the magnetic field and v_f the phase velocity (c in vacuum).

Historically (see Figure 1.4), the concept of the EM waves has evolved, among others, from

- the mathematical formulation of the laws of diffraction (e.g., by *A. J. Fresnel*);
- the mathematical formulation of the experimentally observed relations of electromagnetics (e.g., by *M. Faraday*);
- the establishment of the axioms of the EM field (by *J. C. Maxwell*).

The concept of the EM waves could later be confirmed in experiments (e.g., by *H. Hertz,* who could generate and detect radio waves), which are the basis of today's telecommunication technology. The application of the principles of electrodynamics (and wave optics) around the end of the nineteenth century has led to the invention of electrical lighting, the first forms of electrical data transfer and of "exotic rays" (see Figure 1.5).

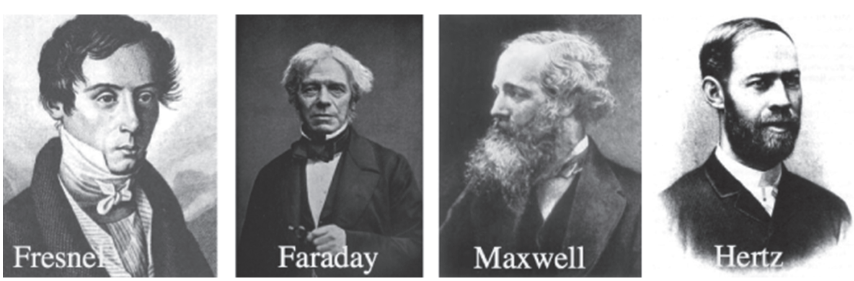

Figure 1.4 Scientists who were instrumental in the development of the concept of electromagnetic waves. (The public domain of http://en.wikipedia.org.)

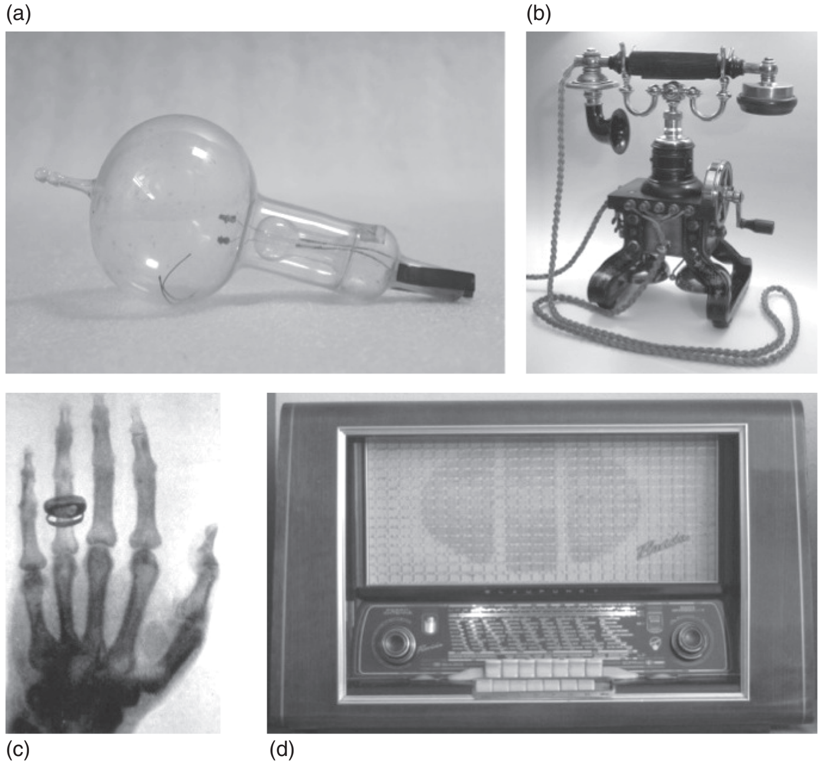

Figure 1.5 Application of electrodynamics and optics around the end of the nineteenth century. (a: The picture of the early light bulb by H. Ellgard was reproduced with permission of the Smithsonian National Museum Of American History. b: The picture of the old phone is by E. Etzold, https://en.wikipedia.org/wiki/Invention_of_the_telephone used under license: CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/. c: X-ray photograph, https://en.wikipedia.org/wiki/Wikipedia:Valued_picture_candidates/File:Anna_Berthe_Roentgen.gif Used under license: CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/. d: Old radio, https://en.wikipedia.org/wiki/Blaupunkt#/media/File:BlaupunktRadio1954.jpg used under license: CC BY-SA 2.0 DE https://creativecommons.org/licenses/by-sa/2.0/de/deed.en.)

1.4 Physics Background of the High-Tech Era

By the end of the nineteenth century, physics was considered a nearly completed discipline, with only a few remaining problems to be solved. As it happened, the latter required a revolutionary extension of the physical concepts. The inventions, following from that scientific revolution, have introduced the high-tech era of the late twentieth and the twenty-first century.

By the buzz word "information society," actually the exchange of electronically processed information through fast optical (EM) channels is meant.[3] Therefore, the devices interesting for electrical engineers today are semiconductor electronics for data processing and storage, optoelectronic elements to produce light or

3 Since a society is a structured group of individuals exchanging information, "information society," without further qualifiers is actually a tautology.

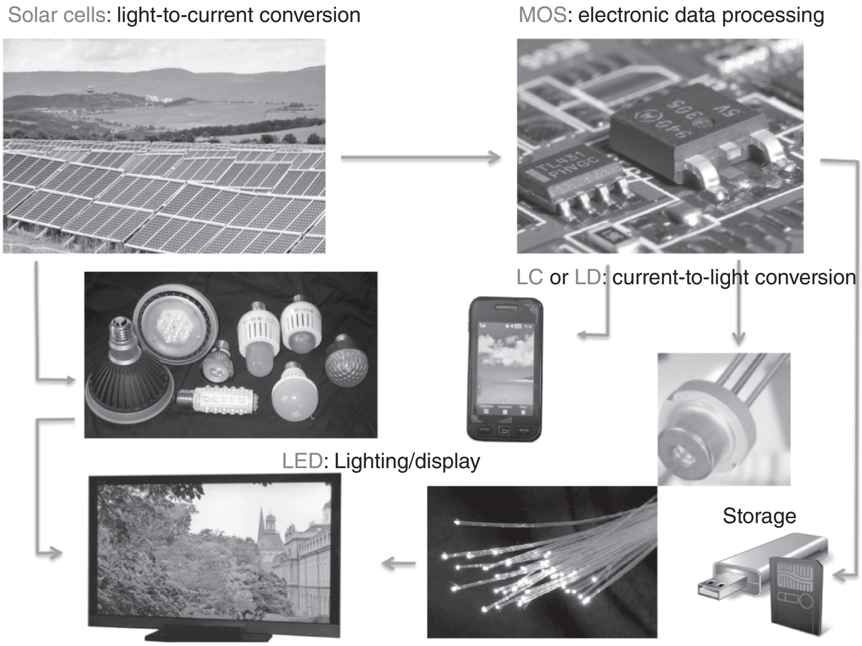

Figure 1.6 The hardware of information technology. Color online. (**solar cells** by Petr Kratochvil, http://www.publicdomainpictures.net/view-image.php?image=3061&picture=solar-power-plant Used under license: CC0 1.0 Universal https://creativecommons.org/publicdomain/zero/1.0/, **IC**s by Magnus Manske, https://commons.wikimedia.org/wiki/File:Chips_3_bg_102602.jpg Used under CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/, **blue laser diode (LD)**, Reproduced with permission of Visible Diode Lasers LLC, A Florida Corporation, **glass fiber** from https://de.wikipedia.org/wiki/Lichtwellenleiter#mediaviewer/Datei:Fibreoptic.jpg Used Under License: CC BY-SA.3.0 https://creativecommons.org/licenses/by-sa/3.0/, **LED lamps** by Geoffrey Landis, https://en.wikipedia.org/wiki/LED_lamp. Used Under License CC BY 3.0:https://creativecommons.org/licenses/by/3.0/, **smartphone & LED display** by the author, and the **SD memory** by Icons-land, Reproduced with permission of Icons Land.)

EM radiation, and displays (Figure 1.6). Lately in the latter, individual pixels are separately illuminated, and light for that is generated the same way as that for interior lighting, namely by light-emitting diodes (LEDs). Electronic information is converted into light modulation by laser diodes or oscillator (LC) circuits, while the reverse process is done by photodiodes. It should be noted that the operating principle of the photodiode is also utilized in most solar cells. The development of these devices has, on the one hand, pinpointed the limits of classical physics and, on the other hand, would not have been possible without its substantial extension.

1.5 Developments in Physics Reflected by the Development of Lighting Technology

The close connection between scientific and technical development can best be followed in lighting technology: from the light bulb, over the discharge lamps, to

Figure 1.7 Stages in the development of lighting technology: the light bulb, compact fluorescence lamp (discharge lamp), and the LED lamp.

the LED lamps (Figure 1.7). As described briefly later, every step of the technical development was coupled to a new chapter in the history of modern physics.

1.5.1 The Light Bulb (Incandescent Lamp)

The operating principles of an incandescent lamp are simple: current heats wire, wire radiates, and the gas fill keeps the wire stable and the bulb clear. The advantages are the low production costs and pollution level, as well as a natural spectral distribution of the radiated energy. The big disadvantage is the very low efficiency (< 20 lm/W, see Chapter 2), which has led to its ban in the European Union. It will be instructive to summarize our knowledge about the physics of the light bulb.

The electric current I in the wire of cross section A is carried by electrons with charge e, mass m, and velocity v:

$$I = envA \tag{1.3}$$

where n is the concentration (number/volume) of the electrons. The velocity of the electrons under constant voltage U in a wire of length l is

$$v = \frac{e\tau}{m}\frac{U}{l} \tag{1.4}$$

because of the scattering of electrons after the mean time τ (see also Section A.4.1). From Eqs (1.3) and (1.4) follows Ohm's law and the microscopic definition of the resistivity R,

$$I = \frac{e^2 n\tau}{m}\frac{A}{l}U = \frac{1}{R}U \tag{1.5}$$

The scattering amounts to friction which produces heat. The Joule heat produced in time t on the resistor R is

$$Q = I^2 Rt = UIt \tag{1.6}$$

Neglecting the gas fill and assuming that only the wire (with mass M and specific heat c_p) is heated, the temperature of the wire T is raised by

$$\Delta T = \frac{Q}{c_p M} \tag{1.7}$$

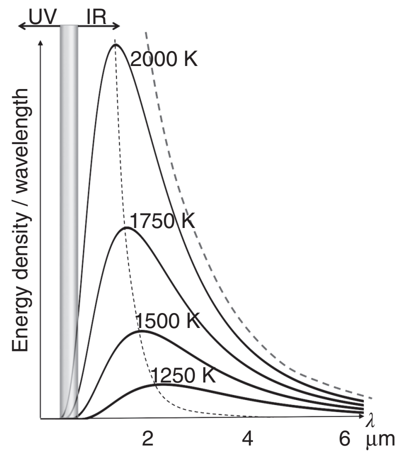

Figure 1.8 Spectral energy distribution of heat radiation. The black solid lines show (somewhat idealized) experimental curves, while the red dashed line shows the prediction of classical physics at $T = 2000$ K. A dotted line shows the shift of the wavelength with maximal energy as the temperature increases. Color online.

We know from experience that heated bodies (e.g., a ceramic stove) radiate heat and light of varying color, that is, a whole spectrum of EM waves. As we discuss in the next chapter, the equipartition theorem of classical physics leads to an energy distribution among different wavelengths λ, which is proportional to $1/\lambda^4$ (see dashed line in Figure 1.8). In contrast, spectroscopic measurements show an asymmetric curve, with a temperature-dependent maximum. The wavelength of the maximum determines the color, shifting from infrared toward ultraviolet with increasing temperature (solid lines in Figure 1.8). This phenomenon is the basis of the contactless temperature measurement by so-called *pyrometers* (see Chapter 2). The measured spectral distribution of the energy cannot at all be reproduced by classical physics. Obviously, if a simple tool, such as the light bulb, cannot be explained in the framework of a physical theory, we must go beyond it.

From Figure 1.8, it follows that pushing the maximum of the energy distribution into the visible range would require a very high temperature, about 6000 K,[4] obviously above the melting point of any metal. The refractory metal tungsten can be heated up to about 3000 K, and at that temperature only $\sim 5\%$ of the radiated energy is in the visible range. The rest only heats the environment. Understanding the laws of heat radiation could explain why this is so, and an accurate mathematical expression for the measured curves would help to design accurate pyrometers.

The explanation for the spectral distribution of the radiated energy, based on energy quanta as described in Chapter 2, was the first step toward quantum mechanics (QM).

1.5.2 The Fluorescent (Discharge) Lamp

The next stage in lighting technology, the discharge lamp (best known today in the form of the compact fluorescent lamp, CFL), is a lot more complicated than the light bulb. Let us consider a traditional fluorescent tube as shown in Figure 1.9.[5]

4 This is the temperature of the sun at its surface. Our organs of sight have developed to utilize the wavelength range radiated strongest by the sun.
5 The CFL is only smaller and wound up, made to fit in the socket of a light bulb.

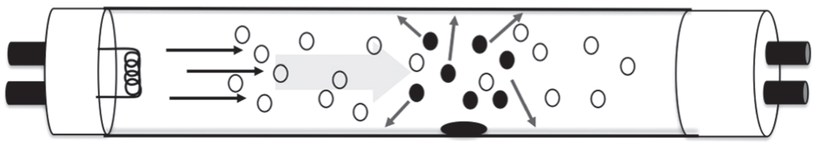

Figure 1.9 Schematic view of a fluorescent tube.

Fluorescent lamps are actually discharge tubes with two electrodes. The voltage between the heated tungsten electrodes induces electron emission and accelerates the electrons. Light atoms of the gas fill are ionized by the impact of the accelerated electrons, leading to an avalanche. The Joule heat produced by the current of the electrons evaporates a mercury droplet. Mercury atoms are also hit by the electrons but, instead of ionization, they are excited into a higher energy state. Returning to the ground state, the mercury atoms emit the excess energy as UV light. The latter excites the molecules of the fluorescent sheet[6] on the inside of the glass tube, making it to "fluoresce," that is, to emit white (or rather whitish) light. To produce UV light, which can be converted into white light by the fluorescent sheet, is very difficult without mercury. Lighter atoms, such as neon, xenon, krypton ("neon lamps"), or sodium, emit only one frequency (color) in the visible range.

This is a complicated system, indeed, with higher production costs and a lot more error sources than the light bulb. Still, the lifetime is about 10 times longer and the efficiency can be between 50 and 100 lm/W, that is, 2–5 times that of the light bulb. On the downside, though, the environmental load is much bigger, and the spectral distribution is ill fitted to the human eye. Optimization requires that we understand the physics of the individual processes; however, the limits of classical physics are quickly reached here too. For one, the voltage necessary to induce electron emission is much lower than that expected from the work function (the energy required for the electron to leave) of the electrode metal.[7] The very fact, however, that a given atom can only emit a few well-defined frequencies, runs completely against the expectation of classical physics (see Chapter 4).

The explanation provided for the spectral distribution of the heat radiation could have remained a curiosity, but to explain these discrete frequencies, again, the concept of quantization was needed. Such a model for the hydrogen atom has led to the questioning of the point-mass-like nature of the electron. Instead, wave-like behavior was attributed to it, and the investigation of that wave has led to the development of QM.

6 "Phosphor" in the language of the trade, although phosphor-containing substances are hardly ever used now.
7 The explanation for that is a phenomenon discovered in quantum mechanics, the tunnel effect: electrons can appear on the other side of a potential barrier without having to "jump" over it.

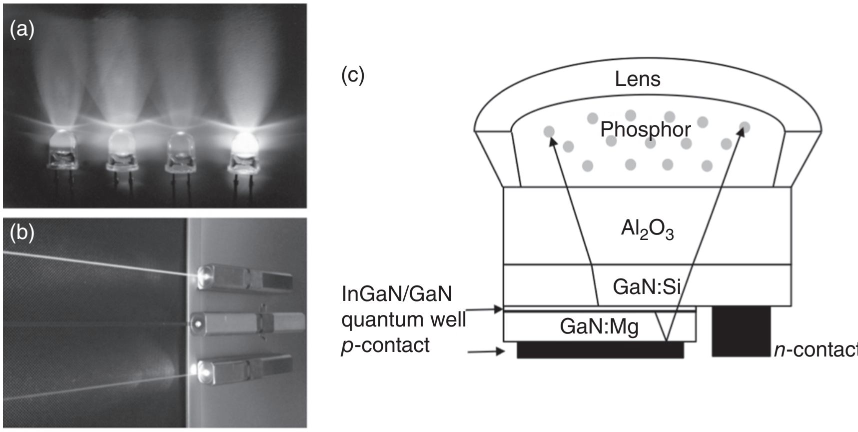

Figure 1.10 Light-emitting diodes and laser pointers of different colors, as well as the schematic (nonproportional) view of a white LED. Color online. (a: Reproduced with kind permission of Fraunhofer IAF. b: https://en.wikipedia.org/wiki/File:Lasers.jpeg#/media/File: Lasers.jpeg Used Under License: CC BY-SA 3.0 https://creativecommons.org/licenses/by-sa/3.0/.)

1.5.3 Light-Emitting and Laser Diodes

While the light bulb and the discharge lamps have evolved parallel with the development of the modern (quantum) physics and influenced that, the LEDs and diode lasers (Figure 1.10) were born as an application of this new physics. Electrical engineers are often using semiclassical models to describe electronic devices, such as diodes and transistors (even at the cost of having to assume an electron mass varying from material to material and sometimes even with voltage), but the development of functioning light-emitting and laser diodes (or, for that matter, solar cells) was only possible by understanding QM.

1.6 The Demand for Physics in Electrical Engineering and Informatics: Today and Tomorrow

The first computers, such as the legendary ENIAC (electronic numerical integrator and computer), were built of circuits with discharge tubes, but this is history by now. The basis of electronic data processing is solid-state (or semiconductor) electronics. The competition between discharge tubes and LEDs for illuminating pixels of a display and for interior lighting is not yet fully decided, but economic factors seem to make the victory of solid-state electronics very likely. Also considering solar cells and lithium batteries (with solid-state electrolytes), it is clear that for large areas of today's electrical engineering the relevant part of physics is the quantum-mechanics-based semiconductor physics. The latter will hopefully be described in a planned book, *Essential Semiconductor Physics for Electrical Engineers*. The QM needed there is described in this book.

The reason why QM is important for electrical engineers goes far beyond the need of semiconductor electronics. QM has changed our perception of matter considerably. The point mass, localized to a single geometrical point, and the infinite wave are both concepts idealized ad absurdum. As we will see, neither can be sustained as the model of a QM particle. Our cognition of the real world had to be expanded substantially. QM means a higher level of understanding and should be part of the world view of anyone aspiring for a B.Sc. in scientific–technical areas.

Beyond that, however, new concepts lead to new applications (such as the paradox of Schrödinger's cat to quantum information processing, or the massless, relativistic electrons of Dirac to ultrafast graphene electronics), which cannot be grasped even approximately without understanding QM. The billions spent on nanotechnology since the beginning of the twenty-first century will eventually come to bear fruit, and will, in the near future, change the work of an electrical engineer considerably. Electrical engineers are mostly interested in integrating devices into efficient and possibly programmable (automatized) systems. However, it is quite obvious that this is not possible without at least a conceptual understanding of the devices.[8] While semiclassical models could help engineers so far, this will certainly not be the case with the new nanoelectronic devices, where the wave nature of the electron is utilized in single-electron switches, or in quantum information processing and encrypting, where the information is coded, for example, into the magnetic properties of a single electron by light. The detailed physics of these future devices (e.g., quantum transport[9]) are, of course, beyond the scope of this book, which was written to accompany a B.Sc. course. The main aim here is to explain the basic concepts of QM, which are applied in today's devices such as *quantum well LEDs*, *cascade lasers*, or *flash memories.* Of course, understanding QM also requires some basic knowledge of classical physics and mathematics. Appendices A and B summarize that. In the following, we see the attempts for answering the questions, which we have raised in relation to the light bulb and the discharge lamp, on the basis of classical physics.

Summary in Short

- Classical physics knows two forms of matter: bodies, which are built of particles, and radiation, that is, waves in the EM field. Particles are treated as idealized point masses, and the EM field is considered as an infinite, ideal elastic continuum.
- It is assumed that the position and velocity of the point mass can, in principle, be accurately determined. The dynamic quantities, momentum, angular momentum, and kinetic energy (which have been defined originally by experiments) can then be unambiguously calculated with the help of the mass.
- The waves of the EM field are characterized by angular frequency and wave number, which determine the velocity of the wave. The energy of the wave is proportional to the phase velocity and to the absolute square of the amplitude.

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8 Just one example from today's power electronics. Silicon carbide-based devices could diminish the energy loss by about 30%. However, unless the systems used for power switching are redesigned, they are far too expensive compared with silicon-based devices with higher loss.

9 For example, http://www.amazon.de/dp/0521631459/ref=rdr_ext_tmb.

- The classical concepts of point mass and waves allow quantitative predictions about the motion of particles and the EM field. They fail, however, if the two are in interaction, as is the case, for example, at the inter conversion of electron currents in light. The hardware of the information technologies (especially nanotechnologies) requires new concepts.

1.7 Questions and Exercises

The questions and exercises listed here refer in part to knowledge from Appendix A.

Problem 1.1 Which kinematic and dynamic quantities can be used to characterize the motion of a point mass?

Problem 1.2 How are canonically conjugate coordinates (q) and dynamic quantities (p) related to each other?

Problem 1.3 What is the basic assumption behind Ohm's law?

Problem 1.4 Demonstrate that a harmonic wave satisfies the wave equation!

Problem 1.5 What is the dispersion relation of light (i.e., of the EM field) in vacuum? Is the phase and the group velocity equal in this case?

Problem 1.6 What is stated in the equipartition theorem of Boltzmann?