# PHYSICAL METHODS, INSTRUMENTS, AND MEASUREMENTS

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## Contents

## Summary

The theme discusses major developments in modern instrumentation and measurements. It first considers fundamental limits, sensitivity and accuracy of measurements, influence of noise on measurement accuracy and signal recovery, in particular, filtering and deconvolution, as well as measurements and standards of time, space, mass and temperature.

Modern imaging systems provide characterization of the bulk and surface state of the object under examination. Different types of microscopes, and tomographic facilities, widely used in various applications, are discussed. Special attention is paid to the analysis of the structure and content of different compounds, one of the major problems of modern technology.

Sources of particles and radiation, detectors and sensors are important parts of any measurement facility. We now have at our disposal various sources of electromagnetic radiation, the sources of nuclear particles ranging from slow particles to relativistic particles, which are produced in different types of accelerators. Updated detecting systems make it possible to register electromagnetic radiation in wide wavelength regions, nuclear particles, acoustic waves, and strength of materials. The main characteristics of any detector are its energy, spatial and time resolution; these features,

playing a main role in a measurement, have to be considered in detail. The measurements at different pressures, temperatures, magnetic fields, and the corresponding techniques of instrumentation are considered.

## 1. Introduction

Physics research is still exciting, intellectually challenging, and extremely relevant to the needs of humankind. Important discoveries are still being made and will continue to be made in the twenty-first century. We have seen a great extension in the use of physical methods in widely different fields, and they are used in all branches of industry, and in medical and biological research. Humane working conditions, long life expectancy, stable supplies of food and energy, increased mobility and leisure are achievements in the second-half of the twentieth century which result directly from the enormous increase in industrial productivity. These have been due to an astonishing rate of technological progress that is based on the achievements of basic research, and in particular physics research.

Measurement is fundamental to the growth and application of science, and progress in instrumentation largely determines the level of civilization. From the cutting of stone blocks to build pyramids and the timing of eclipses to inaugurate religious ceremonies, to the counting of blood cells and the determination of the shape of the earth from satellite orbits, the methods and techniques of measurement have been extended and improved and our dependence on their reliability has increased.

Physics has not only initiated new technologies but has provided the basis for important advances in the life sciences, medicine, chemistry, and the geo-sciences. Moreover, physics is part of our cultural heritage; it answers the most fundamental questions as to the structure of matter, the property of materials, the birth and fate of our universe, and the origin of life on our planet. It contributes to our understanding of the environment and of the place humanity occupies in nature.

The ever-increasing demand for the purity of initial materials in modern science and technology in turn demand chemical impurities as low as one part in $10^{12}$. Interest in trace elements, especially in biological and environmental systems, has been steadily increasing during the last few decades. Important fields of interest are animal, human, and plant biology, food production, medicine and environmental pollution. The interest in trace elements covers toxic as well as essential elements, some of which may also occur in toxic concentrations. Another important aspect of trace elements in both organic and inorganic matrices is that they sometimes display a specific pattern (often called a fingerprint), which may be typical of the origin or the history of a sample.

Viewed from the start of the twenty-first century, some of the most important areas in research in the next hundred years will be in climate change, new energy sources and energy storage, new materials, information technology, transport, health, and environment.

The science, technology and innovation system plays an increasingly important role in creating wealth, thus acting as a driving force in social development. Knowledge has acquired an external value.

## 2. Physical units and fundamental constants

### 2.1. Definition of units

Any experiment deals primarily with the determination of numerical values to be assigned to physical quantities or physical phenomena. These numerical values are obtained in two basically different ways. On the one hand we have simple counting, in which a sequence of events is set into one-to-one correspondence with the natural numbers; on the other, we have a comparison of two similar physical magnitudes. The value of a physical quantity (as distinct from an enumeration of events) is determined by using a standard magnitude and finding the ratio of the desired magnitude to the standard. This standard is the { \ it unit}  by which the desired quantity is measured. The ratio of these two magnitudes is usually noncommensurate.

Although physical laws allow one to define one unit in terms of others, there must be a fundamental set of units that cannot be connected by physical law. In this sense these units are independent. The number of independent units depends on the state of our knowledge of physics; thus, prior to the development of the mechanical theory of heat and statistical mechanical description of gases, temperature was a physical quantity unrelated to length, mass, and time, and hence the degree (on whatever scale) was an independent unit. It is now possible, although not always convenient, to express temperature in terms of the random kinetic energy per molecule. The experimentally determined proportionality constant that relates temperature and energy is Boltzmann’s constant.

In 1960, an international committee agreed on a set of definitions and standards to describe fundamental physical quantities. This system of units, based on the metric system, is known as the SI (Système International). The units of mass, length, and time are the kilogram, meter, and second, respectively.

*Length:* In A.D. 1120  the king of England decreed that the standard of length in his country would be the yard and that the yard would be precisely equal to the distance from the tip of his nose to the end of his outstretched arm. Similarly, the original standard for the foot adopted by the French was the length of the royal foot of king Louis XIV. This standard prevailed until 1790, when the legal standard of length in France became the meter, defined as one ten-millionth of the distance from the equator to the North Pole.

There have been many other systems developed in addition to those discussed above, but the advantages of the French system have caused it to prevail. However, in October 1983, the meter was redefined to be the distance traveled by light in a vacuum during a time of 1/299,792,458 second. In effect, this latest definition establishes that the speed of light in a vacuum is 299,792,458 meters per second.

*Mass:* It was originally intended to define the unit of mass (kilogram) as the mass of one cubic decimeter of pure water. This definition has, however, been abandoned in favor of standards which are more easily measured and preserved. The SI unit of mass, the kilogram, is defined as the mass of a specific platinum-iridium alloy cylinder kept at the International Bureau of Weights and Measures at Sèvres, France.

*Time:* The third fundamental physical unit—the second—was primarily defined through the duration of the solar day. The mean solar day, which is the average interval between successive meridian passages of the sun, is divided into 86,400 seconds. The definition of the second must of course be implemented by techniques that can measure time to an accuracy required to make this definition significant. In 1967, the second was redefined to take advantage of the high precision obtainable with a device known as an atomic clock, which uses the characteristic frequency of the cesium-133 atom as the "reference clock." The *second* is now defined as 9,192,631,770 times the period of one oscillation of the cesium atom.

## 2.2. Temperature

Temperature has an important physiological significance. The association of a second bodily sensation, in addition to vision, with a glowing, fiery object must have developed very early in the experience of the race. It differs from vision among other things in the fact that every part of the surface of the body appears to be sensitive to it. The names for heat or warmth appear early in all civilized languages, and interest in the physical phenomena connected with the sensation likewise occurs in the primitive science of all peoples. As a matter of fact, the word "temperature" goes back to the Latin *temperamentum*, and is thus closely associated with Aristotle's famous four qualities: hot, cold, wet, and dry.

The inventor of the first practical thermometer used as such was Galileo, and this event took place in the beginning of the seventeenth century. The instrument consisted of a small bulb attached at its opening to a long straight tube of narrow bore. When the open end of the tube, held vertically with the bulb uppermost, was immersed in colored water or spirits in an open dish, and the bulb was warmed with the hand, the expansion of the air in the bulb caused bubbles to appear in the surface of the liquid in the dish. When the hand was removed and the bulb cooled, the liquid moved up the tube (see Figure 1). The motion of the meniscus of the liquid as the bulb is brought into varying thermal environments provides an indication of (to use Galileo's own words) "the degrees of heat and cold." Unfortunately, as a thermometer, even if graduated, it would not be completely effective, since the height of the liquid column also depends on the atmospheric pressure. In fact, it would serve more adequately as a barometer if the temperature was kept constant.

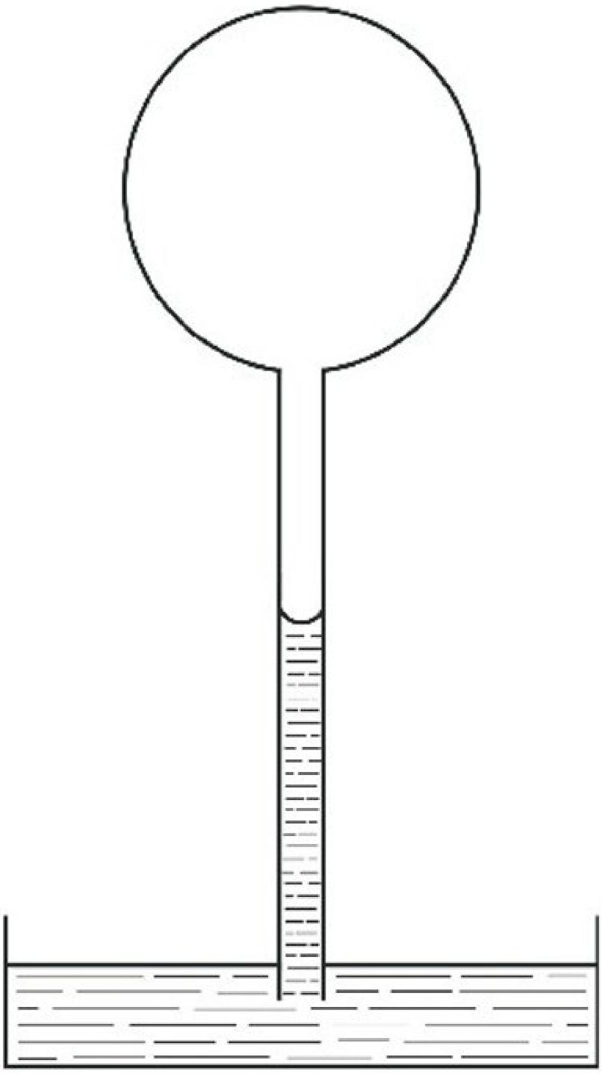

Figure 1. Galilean thermometer

Thermometry enters the modern age with D. G. Fahrenheit, the Dansiger who spent most of his life in Amsterdam. In his papers he described his mercury thermometer and its three fixed points provided respectively by, first, a mixture of ice, pure water, and ammonium chloride (which he took as the zero point), second, a mixture of ice and pure water (32°), and third, the temperature of human body (96°).

Following Fahrenheit, the Swedish astronomer Celsius in 1742 devised a mercury thermometer in which the interval between the readings for melting ice and steam at standard atmospheric pressure were divided into 100 equal parts, with the lower reading marked 100° and the upper 0°. In 1850, however, Märten Stromer reversed the fixed points and produced the centigrade scale in the form we know it today.

Thermometers are devices used to define and to measure the temperature of a system and they all make use of a change in some physical property with temperature. These include changes in:

- the volume of a liquid
- the length of a solid

- the pressure of a gas held at constant volume
- the volume of a gas held at constant pressure
- the electric resistance of a conductor
- the color of a very hot object.

A temperature scale can be established for a given substance using any one of these physical quantities.

The most common thermometer in everyday use consists of a mass of mercury that expands into a glass capillary tube when heated. The thermometer can be calibrated by placing it in thermal contact with some natural system that remains at constant temperature. One such system is a mixture of water and ice in thermal equilibrium at atmospheric pressure, which is defined to have a temperature of zero degrees Celsius, written as 0 °C. Another convenient system for calibrating a thermometer is a mixture of water and steam in thermal equilibrium at atmospheric pressure. The temperature of this system is 100 °C. Once the mercury levels have been established at these two points, the column is divided into 100 equal segments, each denoting a change in temperature of 1 °C.

Thermometers calibrated in this way do present problems, however, when extremely accurate readings are needed. Another problem of any thermometer is its limited temperature range. All scientific and applied problems of thermometry are discussed in detail in the special article of this theme ("Temperature: techniques and instrumentation," EOLSS on-line, 2002).

Temperature is a quantity that takes the same value in two systems that are brought into thermal contact with one another and allowed to come to thermal equilibrium. This statement already provides the basis for thermometry. The essentia1 ideas of thermal contact and thermal equilibrium are present; what is lacking is any indication of how a numerical value may be associated with the quantity temperature.

## 2.3. Data Processing

The results of experiments and their reliability have to be presented and assessed in an objective way. In a concise expression of the results of the measurement of a physical quantity, three pieces of information should be given: a number, a numerical statement of reliability, and an appropriate set of units. The number is generally an estimate expressed in a finite set of units reflecting the limited accuracy of physical measurement. For the estimation of the best value of the desired quantity and of the significance of the result, statistical techniques are used. The term "best" and "significant" should be understood in a technical sense: that is, "best" and "significant" according to some statistical criterion. In other words, statements about the reliability of a measurement require assessment of the accuracy and of the precision of the work.

## 2.4. Fundamental Constants

The group of constants that are conventionally known as the fundamental physical constants include the elementary charge $e$, the electron mass $m_e$, Planck's constant $h$, the velocity of electromagnetic radiation in free space, the Avogadro constant $N_A$, and the proton mass $m_p$. The addition of two further constants, the Boltzmann constant $k$ and the universal gravitational constant $g$, produces the larger group known as the fundamental constants of physics.

Since fundamental constants are so widely used, it is necessary that their values are known with greater precision that most scientists require. At first sight, this might appear unlikely but it is important to remember that measurements being made today will in some cases still be referred to by scientists in the distant future.

Precise numerical values for fundamental quantities such as charges and masses of particles are required to compare predictions of theories with corresponding measurements. Parameters like magnetic moments or lifetimes can be derived from theories, and any discrepancy from precise experimental values indicates the limitations of a theory. The comparison of properties for particles and antiparticles represents a test of fundamental symmetries in physics. These are some of the motivations for the continuing effort to determine particle properties with increasing precision.

Although measurements of the fundamental constants date back to the seventeenth and eighteenth-century determinations of $c$ and $g$, the field began to blossom only after 1900 with the onset of the modern era of physics. Great progress has occurred since the Second World War as a direct result of war-time technological advances in the fields of electronics and microwaves. In addition to $c$ and $g$, other constants measured between 1900 and the Second World War include $e$ *b*y means of R. Millikan’s oil drop experiment; the Faraday constant, *f*, using iodine- and silver-based coulometry; the Avogadro constant, $N_{A,}$ by means of an x-ray technique; and the ratios $e/m_e$ and $h/e$. Important post-war determinations, mostly related to atomic physics, include the proton gyromagnetic ratio, $d_p$; the proton magnetic moment in nuclear magnetons, $\mu_p/\mu_n$; the free electron *g*-factor, $g_e$; and the splitting of atomic hydrogen which, in combination with theory, leads to values of $\alpha$.

In general, the accuracy of fundamental constants determinations has continually improved over the years.

A substantial part of high-precision measurement is based on the technique of particle traps, especially ion traps. These were developed in the early 1930s by F. Penning but have been brought to fruition in the past two decades by an enormous increase in detection sensitivity, down to single particles, and by novel methods that reduce the energy of stored particles to very low temperatures. The extended observation time for stable particles under well-controlled conditions and the low energy to which the stored particles can be cooled reduce the uncertainties of measurements to the sub-parts per billion region. Mass comparisons at this level as well as determinations of magnetic moments test fundamental symmetries and allow comparison to calculations of higher-order terms in quantum electrodynamics.

## 3. Electricity and Magnetism

### 3.1. Electrostatics

The earliest known study of electricity was conducted by the Greeks about 700 B.C. By modern standards, their contributions to the field were modest. However, from these roots have sprung the enormous electrical distribution systems and sophisticated electronic instruments that are so much a part of our world today. It is apparently began when someone noticed that a fossil material called amber, when rubbed with wool, would attract small objects. Since then we have learned that this phenomenon is not restricted to amber and wool but occurs (to some degree) when almost any two nonmetallic substances are rubbed together, and we call such a process electrostatic induction.

The principles of electrostatics are used in various applications. In particular, the process of charging by induction is widely used in the devices that are sometimes called static machines. The most commonly used electrostatic generator was invented in 1930s by R. J. van de Graaf and utilizes a high-speed rubberized-fabric belt to transport the charge. These generators are used extensively in nuclear physics research.

Below we examine electrostatic precipitators, which are used to reduce the level of atmospheric pollution, and the xerography process, which has revolutionized imaging process technology.

*Electrostatic precipitator:* The electrostatic precipitator is used to remove particulate matter from combustion gases, thereby reducing air pollution. It is especially useful in coal-burning power plants and in industrial operations that generate large quantities of smoke. Current systems are able to eliminate approximately 90 percent (by mass) of the ash and dust from the smoke.

Figure 2 shows the basic idea of the electrostatic precipitator. A high voltage (typically 40 kV to 100 kV) is maintained between a wire running down the center of a duct and the outer wall, which is grounded. The wire is maintained at a negative potential with respect to the wall, and so the electric field is directed towards the wire. The electric field near the wire reaches high enough values to cause a discharge around the wire and the formation of positive ions, electrons, and negative ions, such as $O^{-}_{2}$. As the electrons and negative ions are accelerated toward the outer wall by the non-uniform electric field, the dirt particles in the streaming gas become charged by collisions and ion capture. Since most of the charged dirt particles are negative, they are also drawn to the outer wall by the electric field. When the duct is shaken, the particles fall loose and are collected at the bottom.

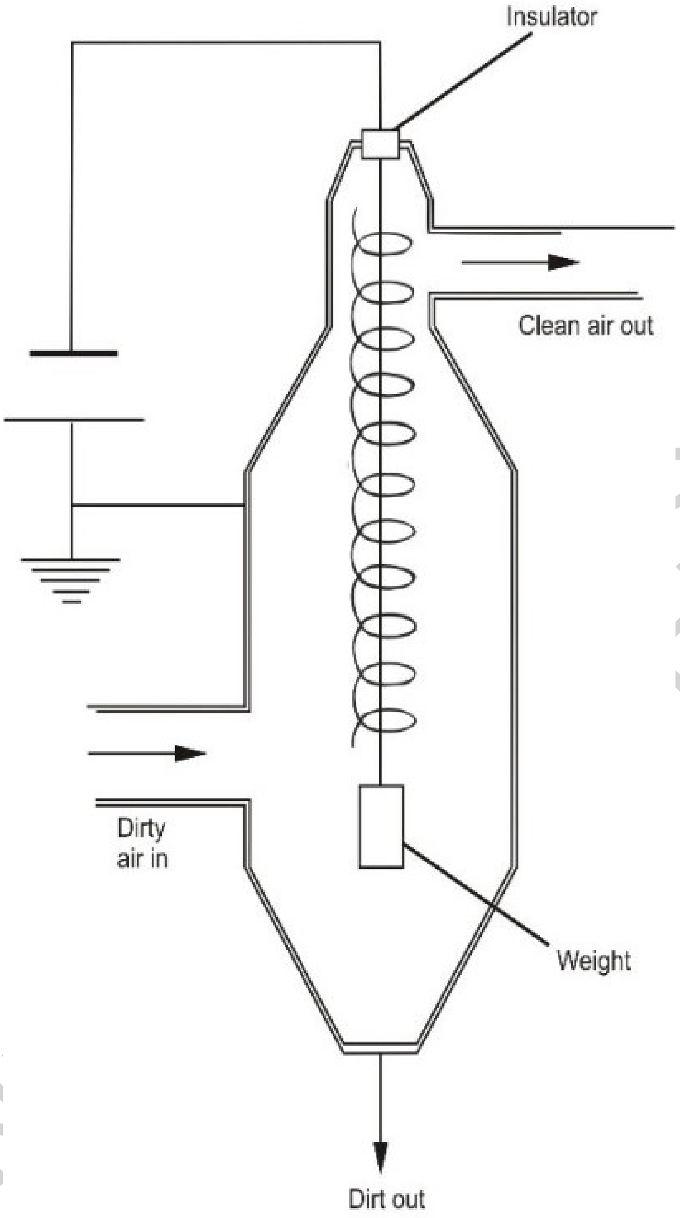

Figure 2. Schematic diagram of an electrostatic precipitator. The high voltage maintained on the central wire creates an electric discharge in the vicinity of the wire.

In addition to reducing the amount of harmful gases and particular matter in the atmosphere, the electrostatic precipitator also recovers valuable materials from the stack in the form of metal oxides.

*Xerography:* The process of xerography is widely used for making photocopies of letters, documents, and other printed materials. The basic idea for the process was developed by C. Carlson, who was granted a patent for his invention in 1940. In 1947, the Xerox corporation launched a full-scale program to develop automated duplicating machines using this process. The huge success of this development is quite evident; today, practically all offices and libraries have one or more duplicating machines, and the capabilities of modern machines are on the increase.

Some features of the xerographic process involve simple concepts from electrostatics and optics. However, the one idea that makes the process unique is the use of a photoconductive material to form an image.

The sequence of steps used in the xerographic process is illustrated in Figure 3. First the surface of a plate or drum is coated with a thin film of photoconductive material (usually selenium or some compound of it), and the photoconductive surface is given a positive electrostatic charge in the dark. The page to be copied is then projected onto the charged surface. The photoconducting surface becomes conductive only in areas where light strikes. In these areas, the light produces charge carriers in the photoconductor, which neutralize the positively charged surface. The charges remain on those areas of the photoconductor not exposed to light, however, leaving a hidden image of the object in the form of a positive surface charge distribution.

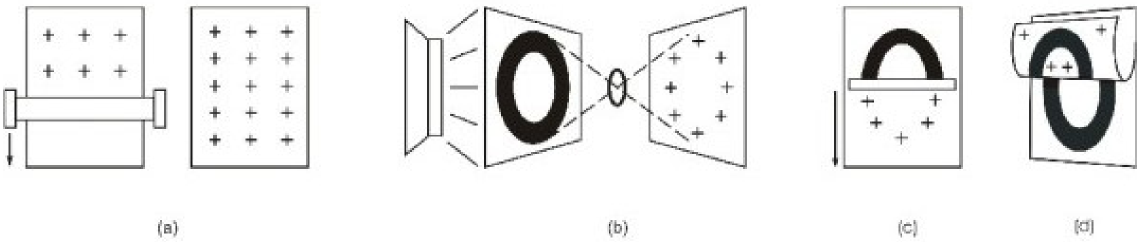

Figure 3. The xerographic process. (a) the photoconductive surface is positively charged. (b) through the use of a light source and lens, a hidden image is formed on the charged surface in the form of positive charges. (c) the surface containing the image is covered with a negatively charged powder, which adheres only to the image area. (d) a piece of paper is placed over the surface and given a charge. This transfers the image to the paper, which is then heated to ‘fix’ the powder to the paper.

Next, a negatively charged powder called a toner is dusted onto the photoconducting surface. The charged powder adheres only to those areas of the surface that contain the positively charged image. At this point, the image becomes visible. The image is then transferred to the surface of a sheet of positively charged paper.

Finally, the toner material is “fixed” to the surface of the paper through the application of heat. This results in a permanent copy of the original.

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## Biographical Sketch

**Yuri Mikhailovich Tsipenyuk** graduated from the Moscow Institute of Physics and Technology (MIPT) in 1962, becoming candidate of sciences in 1969, and doctor of physico-mathematical sciences in 1979. From 1961 until the present he has worked at the P. L. Kapitza Institute for Physical Problems, Russian Academy of Sciences, and is now the leading scientist of this Institute. In addition he is Professor of Physics of the Moscow Institute of Physics and Technology. His scientific interests include: electron accelerators, fission of atomic nuclei, activation analysis, investigation of the solid state by neutron scattering, and superconductivity. In 1997 he was made Soros Professor and in 1997 he became a Member of the New York Academy of Sciences. He has published more than 120 papers in scientific journals, and is the author of three monographs: “Physics of Superconductivity” (in Russian, 1995, MIPT Publishing, Moscow), “Nuclear Methods in Science and Technology” (IOP Publishing, 1997), and “The Microtron: Development and Applications” (Harwood Academic Press, 2001), in addition to being the co-author of a textbook on general physics for high schools, *Basics of Physics* (Moscow, Fizmatlit, 2001).