The ensemble of possible and existing nano-objects and nanomaterials is treated as a multilevel multidimensional system. We introduce the quantitative and qualitative characteristics of elements of the system and give a graphical representation for it. A systems approach makes it possible to establish a basis for a continuously updateable and refineable database including the important properties of nano-objects and their interconnections. Creation of such a database is expedient for dynamic data support of nanometrology in its fundamental and applied aspects.

Key words: nanoparticles, nanotechnology, systems approach.

Nanotechnology, as an ensemble of methods and devices making it possible to controllably create and modify objects including components smaller than 100 nm, having fundamentally new qualities and able to be integrated into full-fledged functioning large-scale systems [Ref. 1, p. 6], is one of the most important and promising directions for development of science and technology. Below, in accordance with this definition, we will use the term nano-objects to collectively mean nanomaterials (including nanoparticles) and the more complex nanosystems, nanomechanisms, and nanodevices containing them. Thus we expand the concept of a nano-object [2, p. 82] in the interests of comprehensive theoretical study and practical applications.

An integral part of all nano projects is metrology, providing a sufficiently accurate and complete quantitative description of the properties of nano-objects and large-scale systems that function based on nano-objects. A natural name for this field of science is nanometrology. This includes adaptation to nanoscales and possibly to new ranges of measurements for traditional quantities such as length, electrical conductivity, etc.; some of the measurements are a direct extension from the micro range. Thus nanometrology to a significant extent is a component and a further development of quantum metrology [3], while nano features can appear even at the classical level.

In future, we should expect that as nanotechnology advances, identification and measurement of numerical characteristics specific to nano-objects and (or) large systems composed of nano-objects [4, 5] will be updated or even pushed to the forefront. In this paper, we outline and discuss some physical metrological problems associated with development of nanometrology.

The Nano-Paradigm. A new paradigm for scientific thinking is taking shape today, drawing considerably on many areas of science: physics, chemistry, information science, biology, etc.

Following already established terminological tradition, it is appropriate to call it the nano-paradigm. Note that this term is sometimes encountered with different shades of meaning that are not exactly defined. It is expedient to assign to the term the meaning that is given to this concept in our discussion here. In this case, we need to bear in mind that the prefix “nano” labels the paradigm without fully reflecting its essence. The main point here is not strictly the absolute value (about $10^{-9}$ m)
but rather the new or substantially improved functional properties of nano-objects, including complex systems. Furthermore, it is appropriate to note the following features of the generally already acknowledged assertion.

The new nano-paradigm is interdisciplinary. It does not override the paradigms of each of the sciences, but has a continuing impact on them. The nano-paradigm consistently considers and treats equally objects of different natures and with different interactions: atoms and various types of artificial atoms (quantum dots, Pauli traps, etc.), the boron lattice and fullerenes, atoms/molecules/nanotubes, molecules/giant biomolecules etc. In particular, separation according to the scientific field, types of interactions, and scale becomes less important, and similar operational functionality and ways to obtain the object are pushed to the foreground. Thus actually ignoring (lacking) differences between living and nonliving at this scale makes it possible to use biological synthesis methods (RNA/DNA analog), to include living cells in nanodevices, etc. Assembly methods are also used that are typical of the macro world, such as, for example, construction kits.

The difference between the three types of objects is partially blurred: devices for creating nano-objects, the nano-objects themselves, and instruments/devices for studying them, making measurements on them, or modeling them. For example, some types of scanning microscopes are used not only to study surface structures of nano-objects but also to assemble them. Some nano-objects can be used as components of computers and at the same time are the objects of computer modeling.

The transition from micro-objects to nano-objects thus is not reduced to further microminiaturization and data compression, although this all exists, but in fact gives rise to a qualitatively new stage of development in the sciences as a whole and in the philosophy of science, i.e., a new paradigm. In the physics literature, we encounter the terms “micro” and “meso” with different meanings depending on context, in particular, for the dependence of kinetic properties on the micro-sizes of metal particles. This does not prevent us from assigning such objects and phenomena to the nano region when the specific features indicated above are present.

Some Prospective Problems. Development of nanotechnologies inevitably generates a number of scientific problems involving nanometrology. The full list is not known and additions will probably be continuously made; we will point out only a few items on that list.

Some divisions of quantum physics are being updated and require further development. This is especially true for accurate quantum measurements, reaching a limit due to the uncertainty principle. Reports of experimental achievement of the limit and observation in this range [1, p. 31] require analysis and verification.

For scanning microscopes and the nano-objects themselves, we need calculations in complicated formulations of the van der Waals force as a special case of the Casimir effect [6]. It is an important contribution to the force pulling the inner wall of a nanotube into the outer wall [7]. The same effect under dynamic conditions appears as contactless friction and radiative transfer of heat between nanostructures [8]. Here the relativistic effect itself may play a role. Note that existing calculations by various methods are quite contradictory.

Material consisting of microstructures (artificial metallic resonators, “metamaterial”) exhibit a unique property: a negative refractive index. There have been reports on fabrication of lenses with practically unlimited resolution [9]. Accordingly, the theory of such optical media needs refinement and revision [10].

Classification of Nano-Objects. Systems Approach. For a number of objective and subjective reasons, the ensemble of objects classified as nano-objects today represents a diverse conglomerate, and attempts have been made to order the ensemble according to various convenient but possibly subjective characteristics. Therefore systematization of nano-objects is an important problem, the result of which should be variable due to their diversity.

It is natural to use as a basis an objective division according to the type of dimensionless characteristic parameters: relative lengths. Let us assume that according to three measurements, the nano-object has the dimensions \(d_1 \leq d_2 \leq d_3\). It has a number of properties with numerical values \(p_n\) and characteristic lengths \(L_n\). Let us introduce two types of dimensionless parameters:

\[
l_n = d_1 / L_n; \quad \delta_1 = d_1 / d_3; \quad \delta_2 = d_2 / d_3.
\]

Obviously \(\delta_1\) and \(\delta_2\) determine the geometry of the nano-object: for \(\delta_1 \to 0\) and finite \(\delta_2\), we have a film, while for \(\delta_1, \delta_2 \to 0\) we have a wire. Here as needed we add other geometric parameters \(s\), for example, the extension of the surface.