The critical differences between microtechnology and nanotechnology are discussed, and the necessity of a new paradigm, nanoarchitectonics, is proposed for the future development of nanotechnology. An important task in material fabrication is to harmonize various factors and effects, and to combine them into functional nanomaterials and nanosystems. It is the way of architectonics rather than that of an individual technology. Therefore, a novel terminology, nanoarchitectonics (nano + architectonics) has been proposed as a new paradigm of materials science and technology on the nanoscale. The statement by Feynman that “there’s plenty of room at the bottom” is really true. With nanoarchitectonics in our hands, we can re-open the door to Feynman’s huge room.

1. How Can We Create New Materials?

Necessity is the mother of invention. Innovation is often driven by necessity in minds. Similarly, the creation of novel materials is the mother of science and technology, i.e., finding and preparing new materials strongly stimulates the progress and development of science and technology. For example, a telescope can be invented only with transparent glass, and the innovation of the light bulb was made with bamboo fibers. A simple material, silicon, opens huge technological success in integrated electric circuits, which is accompanied by a social reform with advanced computers. Certain semiconductive materials create lots of technological innovations, such as blue light light-emitting diodes (LEDs).

Methodologies on developing functional materials and/or function developments of materials can be roughly categorized as follows: i) traditional materials syntheses; ii) fabrication of artificial structures; and iii) emerging science and technology such as topological control. The first methodology is based on material creation through control of sequences, arrangements, and configurations of atoms. The preparation of new inorganic materials through the concept of condensed matter physics and the synthesis of novel organic compounds by organic chemistry are typical examples. This methodology can be regarded as a typical way of traditional materials science. When we find such materials, we may think that they are new materials. However, there is a possibility that these materials already exist within the laws of nature. Nature is waiting for our findings and we come to reach this desirable answer.

The second methodology is fabricating artificial heterostructures, such as heterojunctions and heteroassemblies, especially with combinations that do not naturally occur. Forming interfacial environments upon contacting and fusing two kinds of materials often results in unexpected functions, such as the quantum Hall effect and interfacial superconductivity. Expansion of this concept also leads to the fabrication of functional device elements, including semiconductor integrated circuits and organic electroluminescence units. They rely on microfabrication technology, with which we can construct structures of artificial materials.

Interestingly, attention to the creation of novel materials systems upon the coupling and joining of separate components historically happened in the fields of chemistry and biology at a similar time to the microfabrication technology. A representative example is the concept of supramolecular chemistry. Supramolecular chemistry is defined as a chemistry beyond the molecule, bearing on the organized entities of higher complexity that result from the association of two or more chemical species held together by intermolecular forces. Supramolecular complexes and assemblies are supposed to have properties far beyond summation of the individual components. Although there are certain differences in system size, the concepts and effects of both heterojunction technology and supramolecular chemistry share the same features. In addition, the creation of novel materials and systems can be found in biological sciences, as seen in chimera proteins and DNA origamis. All these materials can be assembled into artificial lattice structures by appropriate techniques, such as layer-by-layer assembly. This progress in chemistry and biology has been fused with microtechnological developments.

The emerging third methodology could be recently found in the final chamber of materials secrets: the topological control of electronic statuses. The importance of topology on the electronic status of materials was theoretically discovered and has been experimentally demonstrated, as seen in topological insulators and topological superconductors. Significant progress on materials innovation with this third methodology is highly expected.

The requirements for further progress in these three methodologies are briefly summarized below. For the first methodology, the tools and methods are already well developed. Even
though new techniques are required in materials synthesis, fundamental ways of thinking in the corresponding fields are well matured and provide good solutions. Although we do not have to worry about further progress in the first methodology, the addition of new techniques from nanotechnology would give new spice to this methodology. The second methodology has so far been developing with heavy contributions from microtechnology. Further development of this methodology requires a transition from microtechnology to nanotechnology. It is also a key to fuse both top-down-type materials creation and bottom-up-type materials preparation, mainly for organic biological materials. The third methodology has to be carried out with scientific and technological considerations of nanometer-sized dimensions. Nanotechnology is a crucial factor for the third methodology. According to these considerations, we can recognize nanotechnology as the most important key concept for future materials science.

Figure 1 summarizes materials science and technology in all dimensions. Macroscopic (visible-size) materials/system construction, including the construction of buildings,
carpentry work, D.I.Y. (do-it-yourself) jobs, and the hobby of plastic modeling all rely on known mechanics. Even large complicated structures and finger-size fine structures can be constructed exactly according to their design drawings and blueprints. If we have materials, tools, and skills, we can make what we want.

Similar concepts and strategies are indeed applicable to material construction on the microscopic invisible scale, using advanced techniques, so-called microfabrication, based on various techniques such as photolithography. Even though objects and systems are not directly visible by the naked eye, fine structures can be fabricated with microscopic structural precision using finely designed tools and sophisticated processes. Ultimate improvements of known construction methodologies have made microfabrication a great success. With microfabrication techniques, we are supposed to construct microscale-objects that exactly reflect their design drawings. On the microscopic scale, we can basically expect structures and properties from their designs.

Next, very small objects, such as atoms and molecules, are considered. The synthesis of organic molecules is often accomplished according to reaction schemes from textbooks and the literature if skill and experience are enough. New routes for molecular contraction are possibly proposed by applying a knowledge of organic chemistry and even by theoretical calculations. The correctness of the proposed schemes is actually demonstrated by experimental efforts. Building of molecules through connecting and breaking bonding can be done exactly according to reaction schemes drawn on paper. The creation of molecules through connecting atoms is also done through logical designs. The preparation of inorganic materials is conducted through rules of lattice structures and other known natural laws.

Unlike for macroscale, microscale, and atomic-/molecular-scale phenomena, the fabrication of materials and constructing systems on the nanoscale or mesoscale regions are not always done decisively according to their design drawings, because uncontrollable and unexpected disturbances and fluctuations have significant effects. The physical phenomena and behavior of materials in these scale regions cannot avoid the influence of thermal/statistical fluctuations and mutual interactions that inevitably occur between components atoms, molecules, and materials. Outputs such as materials structures and properties are not simply determined by known inputs. A design drawing that we make is not an omnipotent guide, and could be a low-valued reference or even a useless piece of paper.

In the nanoscale region, an input signal to a particular target may also provide perturbations to surrounding moieties or components that cause additional mutual interactions. Therefore, in the nanoscale region, the synthesis and fabrication of materials and/or using nanoscale components are significantly different from the decisive and planmable fabrication in the microscale region. For materials fabrication on the nanoscale, concerted harmonization of various interactions and effects are necessary, together with many kinds of techniques and tricks to control materials organization, and stimulating spontaneous processes such as self-assembly/or organization. Techniques have to include control during atomic/molecular manipulation, organic chemistry and physico-chemical reactions, and the application of external physical stimuli. These combined efforts correspond to architecting work rather than to a simple assembly of techniques (technology).

The essence of nano is different from that of micro. We may have misinterpreted the true meaning of nanotechnology. It is not a superior version of microtechnology.

3. Nanoarchitectonics Has Been Invented

As mentioned above, nanotechnology is not a methodology based on a simple advancement of microtechnology. The quality, meaning, and significance of nanotechnology are different from those of microtechnology. However, these two technologies are unfortunately mixed in many cases. In order to fix this point and correct a paradigm shift, a proposal with novel terminology must be done. An important task in material fabrication is to harmonize various factors and effects, and to combine them into functional nanomaterials and nanosystems. It is the way of archit ectonics rather than that of an individual technology. Therefore, a novel terminology, nanoarchitectonics (nano + architectonics) has been proposed as a new paradigm of materials science and technology on the nanoscale. This terminology with this meaning was first used by Masakazu Aono in the year 2000 at the 1st International Symposium on Nanoarchitectonics Using Suprainteractions in Tsukuba, Japan. In scientific literature, Hecht first used this terminology in a title in 2003.

Nanoarchitectonics aims at opening a new paradigm of nanotechnology with the following key concepts. They are also tools for the way of nanoarchitectonics.

i) To create reliable nanomaterials or nanosystems by organizing nanoscale structures (nanoparts) even with some unavoidable unreliability.
ii) To note that the main players are not the individual nanoparts but their interactions, which cause a new functionality to emerge.
iii) To recognize unexpected emergent functionalities that can result from assembling or organizing a huge number of nanoparts.
iv) To explore a new theoretical field where conventional first-principles computations are combined with novel bold approximations.

In recent years, nanoarchitectonics has begun to spread into many fields and become a common and basic concept, as seen in nanostructured materials, supramolecular assemblies, hybrid materials, fabrication methodologies, energy and environmental sciences, device and physical application, and bio and medical applications. As seen in these developments, it is clear that nanoarchitectonics is not limited to simple atomic and molecular manipulations and can be widely applicable for materials science. The latter concept is especially called materials nanarchitectonics.

On the other hand, creation of nanoscale materials and systems often leads to finding unexpected properties. The latter are based on mutual interactions between components where
unusual effects based on specific structures, environments, orientations, and organization can be found with a high probability. We might not know most of these possible findings. The statement by Feynman that “there’s plenty of room at the bottom” is really true. At the nanoscale, there are still many things awaiting discovery. Unfortunately, so far, we have misunderstood the true meaning of Feynman’s word because of conceptual mixing between microtechnology and nanotechnology. However, with nanoarchitectonics in our hands we can re-open the door to Feynman’s huge room.

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