1. A Roadmap to "Nano"

1.1 What is Small?

The title of this section possesses an ill defined question. For instance the earth might be small compared to the sun but some stars are mor than a 1000 times larger than the sun, which makes the sun a small object! Thus a need for a length scale for comparing sizes is eminent to ask whether an object small or large. Size of the observable universe is about 10^{27} meters and the smallest theoretically meaningful length is the Planck's length, about 10^{-35} meters. Another natural length scale is the speed of light. As it doesn't change in any reference frame, speed of light is an important unit of measure of length. Now, since we defined length scales and boundaries we may ask what small is. A better defined corollary to this question is "Are the laws of physics same throughout all the length scales?". The answer to this question is most probably yes! It should be noted however that the models we use for the physics can be different. In this chapter we will try to understand what changes when the certain lengths become smaller compared to relevant quantities.

1.1.1 Length Scales in Nature

There are a number of constants that are fundamental to the physics that don't change over length scales and cannot be written in terms of more fundamental constants. Among these, Planck's constant, $\hbar$ and the speed of light, c are the most fundamental ones and with the recent implementation of the standards, they now define what a meter and a gram is. However, even these constant are sometimes not too relevant to the problem in consideration. For instance, electrons in a solid may show very different behavior based on the effective field they are under in various materials. Thus, in certain class of materials, even at nanoscale we don't observe any quantum effects while these effect become dominant in some other even at hundreds of nanometers. Thus, comparative length scales are crucial particularly in solid state systems.

We can extend this discussion by introducing the concept of mean free path in solids. It is crudely speaking the average distance an electron travels before experiencing a momentum change. If the mean free path of electron is comparable to the relevant device length, for instance, the electron transport will become ballistic rather than diffusive.

1.2 What is a Nanometer?

"Nano" comes from the Greek word "$\nu\alpha\nu o\sigma$" that means dwarf. It makes the quantity that it comes in front a billionth of the value. For instance nanometer is one billionth of a meter i.e. 1 nm $= 10^{-9}$ m. Same rule applies for the other units. Why nanometer is an interesting length? The reason can be easily understood from Figure 1.1 below. Upon going from micrometers to nanometers an unusual world starts to emerge. To exemplify you can imagine how a mosquito can float on the surface of the water. Although we are accustomed to think that we can scale things, without any change in the governing physical laws, the magnitude of forces and their effects become significant at smaller scales. Another popular example to this might be fire. Can you have tiny candles with smaller flames? The answer is no as the shape and the size of the flame is determined by factors like the temperature of the flame, conduction and convection properties of the air and so on.

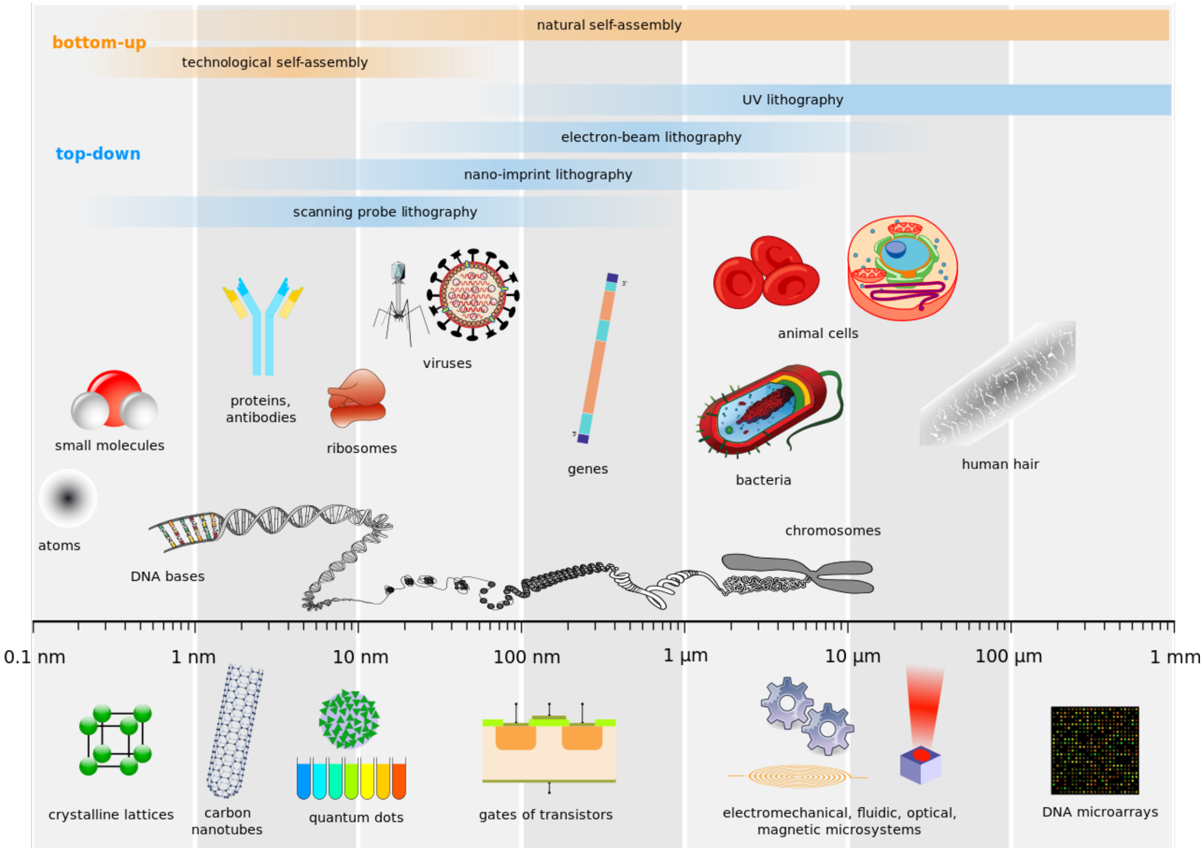

Figure 1.1: Chart shows size scale of both biological and man made structures. (Courtesy of Wikipedia)

Besides such changes in the relative magnitudes of the physical quantities, a physics that don't manifest it self in the macro world starts showing its effects. As we will see in the following chapter, quantum mechanical phenomena will become dominant in dictating the governing dynamics. Thus, when we treat electrons for instance as small billiard balls following the Newtonian "model" of the universe, we fail to understand many properties of the materials.

Before going into the physics at nano-scale, it is essential to understand how we ended up trying to understand the materials at nanometers. In the next section we will try to understand what enables nanotechnology studies in brief.

1.3 What Enables Nanotechnology?

One of the earliest use of nanometer sized materials is probably the use of gold and silver nanoparticles as coloring agent in ceramics by the Romans more than 1500 years ago. Although there are some other uses of nanomaterials, the true explosion in our interest in miniaturization has begun with the discovery of the transistor and the integrated circuits. Of course any fields of science roots to physics, as physics is the basis for understanding how nature works. As for the understanding of science at nanoscale, physics plays an important role. However, what enables nanotechnology is not a question that can be answered in one sentence. Nanotechnology is more of an collective effort of many disciplines such as physics, chemistry, biology and for the question in mind a proper treatment of all these three major disciplines has to be considered in detail. Thus we can say nanotechnology stems from a deeper and more mechanistic understanding of fundamental working principles of various fields. We can safely say that the nanotechnology has its roots in quantum mechanics. After a more accurate description of the nature, we started understanding solids which led to a better understanding of solids. Ideas in quantum mechanics enabled the electron microscopy. Understanding the quantum nature of fluids resulted in better cryogenics. With these ingredients we were ready for nanotechnology. If you read the manuscript of Richard Feynman's 1959 talk at American Physical Society meeting in Pasadena on December 1959, you will realize that the ideas he presented there are so fresh, it almost seems like the talk is delivered on a few years ago. So, at that time the at the idea level, ingredients required for nanotechnology was present. A better understanding of fabrication, characterization techniques and the fundamental principles have led us to the study of nanotechnology. At the moment, nanotechnology revolution is fueling itself. With nanoscience and nanotechnology better computers, better fabrication methods and better characterization tools are becoming widely available to do better nanoscience and nanotechnology.

1.4 Difficulties at a Whole Other Level

As the size of the matter is reduced, the surface starts becoming more important. Interaction between nanometer sized objects start to be dominated by electrostatic and short-range interactions. Reynolds number becomes extremely small. Quantum effects start dominating the electronics. Nanostructures agglomerates and in certain cases they are too small to be characterized by many tools. This list can be extended by many such examples. We can categorize the difficulties in four major classes:

- Quantum effects
- Enormous surface energy due to large surface to volume ratio
- Characterization challenges
- Fabrication challenges

However, especially the first two items in the above list are also the reason why nanoscience and nanotechnology never stops surprising people.

Quantum Effects

Quantum world is a different one from the world we are accustomed to. Particles can tunnel through energy barriers. There are probabilities rather than deterministic results. Observer becomes an inherent part of the system. Energy can become in discrete levels. All these quaintness of quantum mechanics results in very distinct differences for the materials properties. Not only these but, proper understanding of many physical properties of materials cannot be possible without quantum treatment of the systems.

Enormous surface energy due to large surface to volume ratio

Surface area of a cube of side 1 mm, has a surface area of 6 mm^2. If we divide the cube to a 1 nm sized cubes than the surface area becomes 60,000,000 mm^2.This radical increase in the surface area results in increased interaction with the environment.

Characterization Challenges

Although we have numerous tools available to study nano-meter scaled objects it is not always straightforward to characterize the properties of the nano-materials. When the individual nanoparticles are in isolation, manipulation of these particles become extremely difficulty. When they are collected together, due to agglomeration or Ostwald ripening properties under investigation diminish.

Fabrication Challenges

Fabrication of nanomaterials can typically be done either by bottom-up or top-down approaches. In the case of bottom-up approach, the nanomaterial is formed from its finer building blocks. For instance atomic layer deposition forms a thin film by deposition alternating layers of atoms on top of each other. This is an example of a bottom-up fabrication. In the case of top-down, the desired nanomaterial is formed from processing a bulk object. Quantum dots defined on a semiconducting heterostructure via e-beam lithography is an instance of top-down approach. In both cases there are challenges for nano-materials to be fabricated.

1.5 Some Popular Examples of Nanotechnology

Nanotechnology is an active research field and it is evolving on a daily basis. For this very reason it is very difficult to present the state of the art in a timeless manner. Here, I give one example of nanotechnology in nature and, fabrication and characterization of nanostructures. **Please study these examples on your own.**

Peacock Feathers

Color we perceive results from the absorption or reflection of certain wavelengths from the material under observation. Typically pigmentation is responsible from most of the color we see. Depending on what wavelengths are absorbed by the molecules in that particular pigment, we see what is reflected off from the illumination source. However, this is not the case for the coloration in a some bird wings.

Atomic Layer Deposition

There are many materials deposition methods available to fabricate nanostructures. Among these methods atomic layer deposition is a revolutionary idea that enables atomic level precision and control in the deposited materials.

Scanning Tunneling Microscopy

Many fundamental operation principals of nanocharacterization tools depend on quantum mechanical phenomena. One method that enabled and revolutionized nanotechnology is scanning tunneling microscopy. It uses quantum tunneling to create images that have subatomic resolution.