# Chapter 3
# Science

## 3.1 Introduction

Science today studies phenomena lasting less than $10^{-21}$ s and phenomena which occurred more than 13 billion years ago; science also studies phenomena occurring over distances greater than $10^{28}$ cm and shorter than $10^{-13}$ cm; that is, science studies phenomena occurring over times and distances varying by a factor of about $10^{40}$ (Fig. 3.1).[1] In those incomprehensible ranges of time and space, the description of the physical world presented by science is most impressive. Based on what we know today everything in this enormous cosmos everywhere is made up of the same microscopic particles, the atoms and their constituents; their behavior is governed by the same physical laws everywhere.

Progressively science presents to us concepts and objects of the physical world which are beyond our usual experience. In fact, most of modern science lies beyond our vision and senses. In science, we learn to know without seeing and what we indirectly see is wonderful in spite our indirect contact with it. For 50 years,[2,3,4,5] I have been studying the slow electron either bound in atoms and molecules or moving freely in gases, plasmas, electrical discharges, accelerators, scientific instruments or quasi-freely in condensed matter; I released it from surfaces, ejected it from atoms, molecules and ions, attached it to atoms and molecules, detached it from negative ions, had it collide with molecules, ions, atoms, and used it to study new features of the atomic and molecular structure – yet I had never seen it. I saw it and I understood its behavior only through its specific properties that identify it as a particle (with specific mass, charge, spin, energy, de Broglie wave length, etc.), and this is scientifically sufficient, for whether modern science presents to us a picture of the physical world, or a picture of our relation to the physical world, our indirect contact with the physical world as it is provided by science is equally beautiful and meaningful.

 
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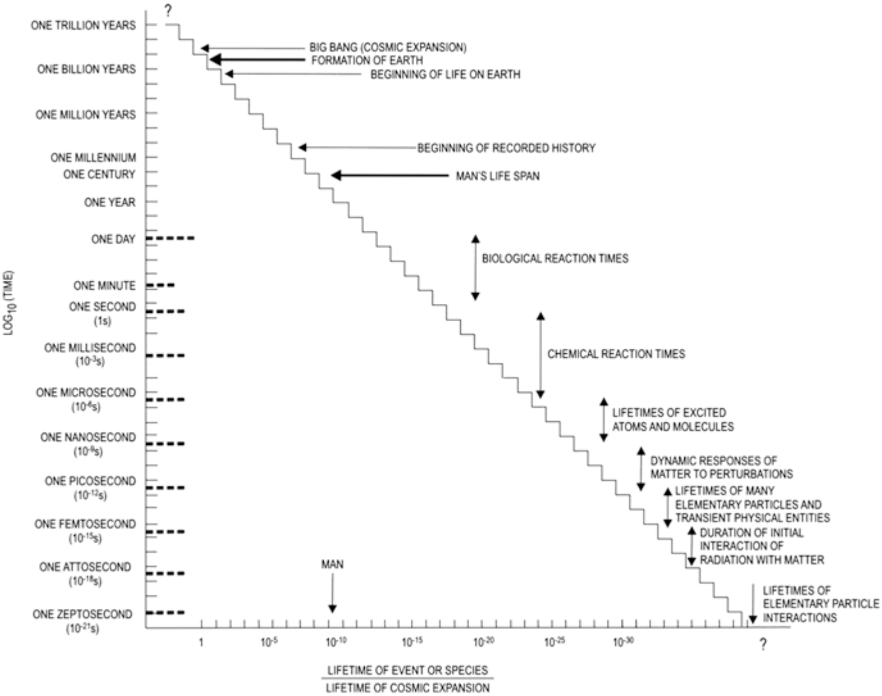


**Fig. 3.1** Lifetime or duration of physical/chemical/biological interactions or phenomena as a function of the ratio of the lifetime or duration of the phenomenon and the age of the universe since the big bang. The scales are logarithmic (every division corresponds to an increase in time by a factor of 10) (based on Fig. 1.3 in Reference 1)

## 3.2 Meaning of Knowing

Verification of knowing must have a source which itself is not in knowing. We need to know what we know and we need to know how well we know what we know, and we need to allow for the things we do not know that might exist. Knowledge can only be looked at from the point of view of the method of knowing. Whether we know through deduction, reduction-induction, or holism, or through inference and faith we are limited. This then instructs caution for all knowledge carries its own limits and is subject to doubt.

### *3.2.1 The Inductive Method of Science*

Our knowledge about the physical world began with the sixth century BC when Thales of Miletus (c. 620–c. 546 BC) asked "What is the world made of?" and he answered, "Water". The question is still being asked and the answer today is of course different, "Energy" (e.g., see References[6,7], Chaps. 1 and 7 and Appendix).

The “natural” philosophers of Ionia – among them Thales of Miletus, Anaximander (c. 610–c. 546 BC), Anaximenes (c. 585–c. 528 BC), Heraclitus (c. 535–c. 475 BC) and Anaxagoras (c. 510–c. 428 BC)[8] – were the first to look for simple principles behind the variety of the observed physical phenomena. The principles sought then were substances; today they are theories and “laws”.

The early natural Greek philosophers dealt with generalizations. Heraclitus taught that there is an underlying unity of the world and argued that the fundamental essence of the cosmos is *change*; he emphasized the generality and continuity of change. “Τα πάντα ρεί” (everything is in a continuous state of flux, in a perpetual motion like a river) he said. Like the old Greek philosophers, the modern physicist reaffirms: nothing is at rest; science deals with change; we live in a restless world permeated by ceaseless change everywhere.[9]

A little later, and in opposition to Heraclitus, the philosopher Parmenides of Elea (c. 515–c. 460 BC) argued that the fundamental structure of the cosmos is unchangeable; *the being* ***is*** and it exists as a whole.

The ancient Greeks accommodated Heraclitus’ and Parmenides’ diametrically opposing views in the most brilliant way, that of *complementarity*. The world *is*, but it *is continuously changing, perennially becoming*.

The holistic approach of Heraclitus and Parmenides was followed by the opposing view of the atomists, foremost Leucippus (c. 480–c. 400 BC) and Democritus (c. 460–c. 370 BC), who taught that the world is made up of definite unchangeable and indivisible substances – which they called *atoms* – moving in a void; the combination and separation of these atoms leads to the visible matter and causes the perennial change and transformation of the cosmos. Democritus’ atomism was the first example of reductionism: *from the cosmos to the parts – the atoms – and from the parts – the atoms – to a construct for the cosmos.*

Atomism itself was opposed by Aristotle (384–322 BC) because it was considered not suited to describe, let alone explain, the order, harmony and the purpose of the cosmos. Aristotle’s philosophy was centered on holism and teleology. The whole he concluded deductively is more than the sum of its parts and it has characteristics of its own which are not reducible to the properties of its constituent parts. There, thus, has been present in ancient Greece a deep conflict between holism (the understanding of the whole as a unified entity) and reductionism (the understanding of the whole based on the knowledge of its parts), which persists to this day.

Greek philosophers, principally Plato (427–347 BC), taught that truth adheres to *axioms*, a priori concepts in the “world of ideas” with indisputable validity. Plato believed that the whole structure of the cosmos could be deduced from such axioms and developed the concept of *deductive reasoning* and the logical techniques for proof. In some way, this approach is analogous to the thinking of some theoretical physicists today who believe that truth is to be found in logical mathematical structures, in mathematical models.

Deduction has since become the philosopher’s powerful tool to the truth, its basic limitation being the universal validity and self-evidence of the axiom. Deduction makes explicit information which already exists in the axiom; the validity of the deduced entity is derived from that of the axiom.[10,11]

The method of modern science is both deductive and inductive. While deduction is a powerful tool to the truth, the power of modern science comes from its inductive method based on the ability of science to reduce and the use of the experimental method to "interrogate" nature under reduced and controlled conditions. This way observations and experimental data are checked for consistency and are harmonized among themselves; they are validated by the known physical laws and are explained and unified by general concepts and theories: *From the experiment, inductively to a general theoretical rationalization, and from the theory deductively to the results of the experiment and to more experiments.* In this two-way inductive-deductive process the agreement between theory and experiment and the experimental confirmation of the predictions of the theory constitute the fundamental criterion for the validity of the theory and its conceptual formalism and foundation.

Systematically, modern science has reduced the physical world to molecules, atoms, nuclei and subatomic particles and based on this knowledge at the most fundamental reduced level succeeded in establishing the physical law and the order of the physical world, based on the validity of the physical law. Through this "reductionist" approach, physical science laid the ground for a unified description of the physical world at the microscopic and, by extension, at the macroscopic scale.

The recognition of the power and the limits of this extension – that is, the recognition of the fundamental interconnections between the properties of the nuclei, the atoms, and the molecules on the one hand and the various forms of matter, the world and life, on the other hand – is most significant. This is because the reduction of the physical world to its elemental constituents and the discovery of the fundamental laws that describe their behavior at the extreme reduced and isolated level of matter, does not lead to its reconstruction based on ***only*** this knowledge. It is hindered, for instance, by the enormous differences in scale and complexity and the interactions a system continuously undergoes with its environment. This is especially significant when one refers to living organisms the behavior of which may be rationalized by new laws over and above the known laws of physics which describe the behavior of their constituent parts. The whole is manifested in the particular, but it has properties of its own.[12,13]

As in ancient Greece, many scientists today have stressed the need to consider holistic properties and teleology issues and have pointed out that neither it is possible to comprehend the basic phenomena of life based on the known laws of physics, nor it is possible to understand man only by a reductionist view of him. The preponderance of scientists today, however, hold the reductionist view, that "*all the explanatory arrows point downward*",[14] that is, everything can be boiled down to molecules, atoms, and particles, life itself included. *This reductionist view of man conflicts with the world-view of a large fraction of society.*

The history of science teaches (see endnote 1) that science progresses in small steps normally based on observations and experimental data and their correlation via the inductive-deductive method – small steps which demonstrate the validity or the inadequacy of existing theories; in the latter case, they call for the introduction of new concepts and new theories. Small steps like the observations of the astronomers of ancient Greece, the calculations of Kepler, and the experiments of Galileo that led to the laws of classical physics of Newton. Small steps, also, like the first experiments which determined the nature of electricity and magnetism, the discoveries of Faraday, the laws of Coulomb, Ampere and Gauss which themselves led to the synthesis of Maxwell, the existence of electromagnetic waves and the speed of light. In a similar fashion, small steps like the absorption and emission spectra of atoms, the ionization of gases by ultra violet radiation, the light emission from hot objects, the discovery of radioactivity, and the discovery of the electron, which led to the special theory of relativity, the quantum theory of light and matter, and the quantum mechanical description of the microcosmos at the most fundamental level. An important part of this process has been the introduction of new concepts such as the concept of the field, electromagnetic wave, photon, quantization of energy, relativity and so on.

Similar schemes can be sketched for biology. One can identify, for instance, the following four important steps in the evolution of modern biological sciences (see endnote 1)[15]: The theory of evolution in 1859 by C. Darwin and A. R. Wallace; the discovery that *DNA* is the genetic material in 1944 by O. T. Avery, C. M. Macleod and M. McCarthy; the discovery of the molecular structure of *DNA* in 1953 by J. Watson and F. Crick and others; the sequencing of the human genome at the very end of the twentieth century by groups of scientists. In biology, the nature of the scientific concepts employed is radically different from that in physics: *evolution is a macroscopic concept and DNA is an incredibly complicated macromolecular structure.*

### *3.2.2 Reductionism and Holism*

Our understanding of the physical world in its extreme simplicity as is provided by the reductionist method of science far exceeds our understanding of Nature at higher levels of complexity. This is because as the complexity of matter increases gradually emerge new properties of matter and new physical phenomena which cannot be accounted for or be predicted by the reductionist method of science. That this is so can be illustrated by the following examples.

**From isolated particles to a system of particles** At the subatomic level, matter consists of a variety of types of particles. While the particles of each type are similar and interchangeable, their behavior as a system cannot be analyzed based on their individual behavior alone. In fact, the behavior of a system of particles depends on the kind of particles the system consists of. Let us consider the kind of particles called "fermions" and specifically the electrons which have a spin equal to 1/2. A collection of electrons obeys Fermi statistics and thus behaves according to the Pauli Exclusion Principle: No two electrons with the same values of their four quantum numbers can occupy simultaneously the same quantum state of a polyelectronic atom. The principle describes the fact that electrons in atoms cannot spiral down into the nucleus, but instead they form a series of shells which surround the nucleus, giving atoms their distinct structure. The number of electrons in the outermost atomic shell produces the chemical valence, which in turn binds atoms into molecules. The properties of the system of these outermost electrons define the kind of atoms and molecules that can exist and thus the kind of materials found in nature.[16] The Pauli Exclusion Principle applies to systems of particles and has little meaning for individual particles. The features it describes are not mere extensions of the properties of the individual particles, although they depend on them (see endnote 16).

Let us look at another type of particles where matter consists of a very large number of neutral molecules, as in room-temperature air (where at standard pressure and temperature the number density of molecules is ~$2.7 \times 10^{19}$ molecules $cm^{-3}$). The thermodynamic behavior of this system of particles obeys Maxwell-Boltzmann statistics and the concepts of gas temperature and gas pressure define experimentally measurable macroscopic properties of the gas (the air). While the macroscopic properties temperature and pressure of the gas are related to the microscopic motions of the individual molecules making up the gas, they are meaningless for the isolated gas molecules; they are new, *emergent properties* of the whole collection of molecules making up the gas. The temperature and the pressure are properties of the entire system of particles and not properties of the individual molecules themselves.

**From isolated atoms to isolated molecules** Atoms form chemical bonds between them when they come sufficiently close together because the *emergent composite structures*, the molecules, are energetically more stable than the separate atoms comprising them. The atoms make something new and different – chemical compounds – with new properties which depend on the properties of the atoms making up the compounds but are not reducible to them. Molecular structure is more complex than the atomic. For instance, the hydrogen molecule ($H_2$) is formed when two hydrogen atoms come close enough together that the orbits of their electrons overlap and the probability of the two electrons being in the same space between the two hydrogen atoms of the hydrogen molecule is large. For these conditions to be satisfied, the electron of the one $H$ atom must be moving in the opposite direction than the electron of the other $H$ atom, that is, the spins of the electrons of the two $H$ atoms must be anti-parallel. Only then the probability of finding simultaneously the two electrons between the two $H$ atoms is large and the negative charge of the two electrons between the two nuclei attracts them together, and a bond between the two $H$ atoms is established. In the opposite case, where the spins of the two electrons of the two $H$ atoms are parallel, the electrons cannot be simultaneously between the two nuclei, the force between the nuclei is repulsive, and the $H_2$ molecule is not formed. This is what is demanded by the law of the lower level of complexity for the electrons.

In the hydrogen molecule, the two electrons not only have different energies, but the hydrogen molecule has different absorption and emission spectra, different ionization energy and new characteristics such as vibrational and rotational structure. The laws of the lower-level complexity systems are seen to determine the kind of higher-level complexity systems possible, but the properties of the higher-complexity systems have no analogy to those of their parts.

Let us consider another molecule of still higher-level of complexity, that of water ($H_2O$). The chemical and physical behavior of the water molecule is determined by its quantum mechanical structure, which itself is dependent on the electronic structure of its constituent atoms *H* and *O*. The water molecule has physical and chemical properties of its own, for instance, an electric dipole moment. In turn, the electric dipole moment and the stereo-chemical structure of the water molecule crucially determine its interactions with other molecules. Water molecules make “hydrogen bonds” with other water molecules (hydrogen-bonded structures), transient clusters comprised of specific numbers of water molecules, complexes around positive ions, around negative ions or around electrons (forming “hydrated” electrons), and so on.[17]

If a few trillion trillion water molecules are put in a glass, the whole assembly of the water molecules, the liquid, acquires a new property, *fluidity,* that none of the water molecules has. Fluidity, wrote Phillip Anderson in an article with the title “More is Different”, is an *emergent* property of liquid water.[18] If, now, liquid water is heated up to 100°C, the same molecules evaporate and the system makes a phase transition to water vapor. If, conversely, liquid water is cooled down to 0°C, the system abruptly undergoes another phase transition, the water molecules stop their chaotic motion and form an ordered hexagonal crystal structure known as ice. These forms of matter are *emergent*; they have no meaning for the isolated water molecules. The transition from the liquid state of matter to the crystalline forms of matter is normally associated with two important *emergent* properties: *order* and *organization*.[19]

Many other similar examples can of course be given and indeed one can extend this type of discussion even to our Galaxy and the entire universe. The whole, the Milky Way Galaxy, with its unparalleled complexity and dimensions has new. *Emergent*, properties – for example, black holes – above and beyond those of its constituent parts; incredible plethora of new phenomena and new properties arising from Nature at this scale of size and level of complexity.

**From inorganic matter to the phenomena of life** The reductionist quest for knowledge in science discussed in the previous sections, is faced with fundamental problems of principle in accounting for the behavior of biological systems. As we have repeatedly said, reductionism deals with the parts, holism treats the systems as wholes. We cannot comprehend the whole without the knowledge of the parts, but we can comprehend the parts without comprehending the whole. In biology, the goal is to understand not what things are made of, but how they are put together and function as integrated wholes; how totally new structures (e.g., the embryo) emerge in the progression from inanimate to animate matter (see endnote 19).

The view that life has been reduced to its molecular basis is thought to have been strengthened by the great recent advances in biochemistry, molecular biology and genomic science. Large molecular structures are normally “loose” systems with many weak bonds between their atoms and with many degrees of freedom which facilitate their transformation into other structures through a multiplicity of rearrangements, mechanisms and interactions that allow their co-evolution with their surroundings. At every level of molecular complexity emerge new structures which change the ability of the system to evolve. In this way, knowledge of the structure of biological molecules becomes the basis for understanding their biological action. It is known for instance that the biological action of macromolecules is affected by the "structured" water of the cell milieu[20]; for example, it affects the way in which macromolecular structures fold and change their shape and, consequently, their reaction mechanisms.

The road from physics to biology is thus obstructed by the extreme complexity of the systems of biology. Many distinguished scientists (e.g., Phillip Anderson (see endnote 18), Edward Wilson,[21] Paul Davis (see endnote 19),[22] Eugene Wigner,[23] Stuart Kauffman[24,25]) support the view that the understanding of the holistic properties and the organizational principles of biological systems will likely be achieved with autonomous laws which deal with complexity and auto-organization of matter, laws above and beyond the known laws of physics. Such basic laws remain unknown.

There remain countless fundamental questions in going from the physical and biological understanding to that of the human person.

### *3.2.3 The Indirect and the Complicated*

The questions about the elements the world is made of, the nature of being and becoming, reductionism and holism, facts versus constructs and ideal forms, creation of constructs, inductive and deductive reasoning, and the way we go from the particular part to the whole, from the simple to the complex, from the small to the big, from the short-lived to the long-lived, from the microscopic event to the macroscopic effect, are all still open-ended; more often than not they are partially answered or unanswered.

Even the experimental measurements we so much rely upon are often convoluted with many variables that make "the experimental results" indirectly-deduced quantities, often remotely connected to the initial measurement or event. It used to be that a scientist's experimental equipment was simple enough for him to claim that it was an extension of himself in his pursue of knowledge. There used to be a time in the past when the scientists made their measurements, analyzed them, interpreted them, deduced their conclusions and little else; all was personal and direct. Today, with very few exceptions, this is so no more: all is impersonal, indirect and remote. Both modern experiments and theoretical computations and simulations are too complicated to keep direct control of, and the knowledge acquired too remote and too indirect. And although, and despite its abstraction and indirectness, such knowledge is "real", it remains a fact that *the new methods of science make direct contact with nature difficult; new methods of learning tend to provide convoluted information.*

Look, for instance, at supercomputing (soon on its way to the exascale, computers that can perform a billion billion ($10^{18}$) calculations per second). Supercomputing is becoming an essential tool not only in physics, chemistry, fluid mechanics, astrophysics, cosmology and material science, but in neuroscience, biological and life sciences, climate change simulations and predictions, and so on. The convoluted nature of the knowledge it provides, often makes direct experimental confirmation difficult. Information technology is revolutionizing how research is done and how researchers interact with each other.

## 3.3 The Nature of Truth and the Image of Reality

Every age of history seeks "the truth". But what is truth? What is the essence of truth? To this old question there is still no simple answer because the answer depends on the context within which the question is being asked and on the method of knowing being used to know. If, for instance, we accept that truth is the concern of both science and faith, what is the nature of the two kinds of truth and what is the relation between them? Independently of the answer, truth is related to freedom and freedom is the essence of human existence. We are, then, instructed to be tolerant of and receptive to the diverse ways in which truth is mirrored in all things and to the methods of knowing.

Science is underpinned by the belief that there is a truth about the physical world that Nature can be made to yield, if only one knows the proper questions to ask. Scientific results then are regarded as something "found by" or "disclosed to" the scientist. Van Fraassen[26,27] sees scientific realism as a belief in a "deep structure of reality", to be revealed by scientific inquiry. We must, thus, in principle, be able to recognize the truth when we reach it, if not before. There is, however, also, the view that "scientific results are to be construed as imprints made by the human mind upon Nature", a view that accepts a level of relativism and subjectivism in the knowledge of scientific truth. Such a view is expressed in the writings of Polanyi[28] and Kuhn[29] and is apparent in the conjectures by Einstein and Bohr about aspects of scientific reality.[30]

Truth is central to science: you can practice science only if you respect the truth. But who defines scientific truth? Scientific truth could be defined as that which scientists affirm and believe to be consistent with the accepted body of scientific knowledge. Scientific truth, then, is found, not given, and it is tested, "subjected to verification". But not all truth is verifiable or complete. Even Aristotle's argument that truth is the agreement with the facts of what is being asserted is not always possible to ascertain. And there are still those[31] who wonder if in a changing universe, the physical laws remain unchanging. Thus, ultimate, absolute, complete true knowledge is not in the court of science; even in science truth is elusive and the true nature of reality may not be amenable to knowing. Although it is in the nature of charge to be subject to the Coulomb force, writes Cartwright,[32] this nature does not in any way reveal *the essence* of charge. Yet, there is scientific knowledge (truth) so well-defined and scientific explanations so thoroughly tested and "confirmed" that they are confidently held and are indeed transformed into powerful useful science-based technologies.

In man's search for truth, the problem lies not with the scientific findings themselves, but rather with the view that there is no truth other than that provided by science. But if a thing cannot be subjected to scientific testing is it necessarily wrong or unimportant? Should we insist on one truth or should we rather concede that there are many kinds of truth, or various aspects of truth, accessible via complementary ways and methods of knowing? Truth we believe is more than what can be accessed by any single known method of knowing. Beyond that which we know with certainty, lay the vast ocean of the unknown and the unknowable, and all knowledge is shrouded in doubt. We are then led to conclude that the wholeness and the unity of truth presuppose true complementarity among the various kinds of knowledge and the methods of knowing.

## 3.4 The Laws and Concepts of Science (Physics)

Let us look at the laws of physics and the concepts and constructs behind them. The laws of Nature, as established by physics, are mostly inductive generalizations of reductionist knowledge; precise quantitative relationships between physical entities found by repeated experiments and observations, reflecting persistent regularities in the behavior of the physical world, which are rationalized deductively with reference to a broader law based on a concept, usually mathematically structured. Concepts, maintains Barrow,[33] are more profound than the physical laws; in the concept of gravity, he writes, "we express not a specific law of physical behavior, but a unitary picture of how Nature works: what holds the world together and yet allows it to move and evolve."

Behind every law of physics there is a concept and, thus, every interpretation and rationalization of physical facts and phenomena, and, consequently, every comprehension of Nature based on the physical law, depends on human concepts. Reality, however, does not owe its existence to concepts. No concept is final; concepts are made and remade, and new concepts evolve as new knowledge is acquired. Such, for instance, is the sequence of concepts from classical physics (particles, waves, forces, etc.), to gravity, electromagnetism, quantum physics, relativity, string theory. True revolutions in science are transformations of the concepts upon which science is based (such has been the case in the work of Galileo, Newton, Maxwell, Planck, Bohr, Einstein and so on) and the resultant unifying power of science. Since all human constructs are subject to change, all knowledge based on physical law however elegant is temporal and incomplete. The physical laws are not rigid; time and again, one physical law leads to and is superseded by another more general and more precise. Nonetheless, the established physical law represents enormous compression of information and on it rests the power of science to predict.

The laws of physics apply across all of science and appear to hold in every part of the universe so far investigated, and in that sense, they are presumed to be universal. They, however, have been established by looking at the physical universe 13.8 billion years after the big bang and are based on knowledge of inanimate matter.

***Source (Object) →Field →Force →Energy Transformation and Flow***

**Fig. 3.2** Fields relate to sources and, through forces, to energy transformation and energy flow

The universality of the physical law – holding for everything, everywhere, and for all times – is, thus, implicit. The physical laws we now know, for instance, may not be applicable under the extreme conditions at the very beginning of the universe. It should perhaps be noted also that the laws of macroscopic matter are seemingly unaffected by the laws of microscopic matter, and, conversely, that the laws of microscopic matter are seemingly unaffected by the laws of macroscopic matter.

Let us then look, by way of example, at just the concepts of the *field* and the *force* which are relevant to the concept of *energy* so frequently referred to in this book. The field relates to a source (an object) and, through the force, it relates to energy transformation and energy flow (Fig. 3.2).

Sources of fields are charges (positive and negative) and masses. Charges or masses entering the field created by the charge or the mass experience a force and gain energy. Fields do not occupy space, but extend throughout space, including vacuum; they contain energy and their strength diminishes as the distance from the source increases.[34] Fields are invisible; they are "seen" by their effects.

*Stationary* charges generate electrostatic fields and *moving* charges (electric currents) generate magnetic fields, and if a magnetic field changes, it generates an electric field. Electric and magnetic fields can be coupled, constituting two parts of a greater whole – an electromagnetic field. The classical concept of an electromagnetic field is one of a smooth and continuous field, which extends indefinitely through space propagating in a wave-like manner, exerting a force on other charges via the so-called electromagnetic interaction. The electromagnetic wave has energy, which is proportional to the frequency of the wave. This classical concept of the electromagnetic field is complemented by the quantum-mechanical concept of the electromagnetic field as a quantized entity, comprised of individual particles, quanta or photons, each having a fixed energy $E = h\nu$, where $h$ is the Planck constant and $\nu$ is the photon frequency; in this picture, then, energy moves discontinuously.

Similarly, mass is a source of field. A mass object establishes a gravitational field around it. The gravitational field created by all the mass in the universe, gravity, pulls on every particle of matter in the universe. Just as in electromagnetism moving charges generate electromagnetic waves, in the theory of general relativity moving masses generate gravitational waves. However, because of the weakness of gravity,[35] astronomical amounts of matter must be moved around to generate waves on a scale that might be detected. Such gravitational waves from a merging two black-hole system have recently been detected.[36,37]

Fields give rise to forces and forces play a vital role in understanding the interactions between the constituents of matter and energy. Indeed, today, all interactions in nature are studied in terms of four fundamental forces – gravity, electromagnetic, strong nuclear, and weak nuclear – mediated by the exchange of particles. What does force have to do with energy? *Forces cause the transformation and flow of energy.*

An increasing number of scientists see the reductionist laws of physics to be limited when applied to the structures of biology and as inadequate to explain the behavior of the complex systems and functions of living organisms (see endnotes 23–25). Wigner (see endnote 23) maintains that the laws of physics would have to be modified drastically if they are to account for the phenomena of life, and Kauffman (see endnotes 24, 25) advises "to go beyond reductionism into emergence."

An increasing number of scientists are then led to ascertain the possibility that there are laws which govern the behavior of complexity and living matter which need well-developed concepts and constructs and a new vocabulary that might include terms like emergence, organization, information, growth, adaptation, genes and so on, suited for biology rather than for physics. These laws are envisioned to be fundamental in the sense that they cannot logically be derived from the underlying laws of physics.

## 3.5 Distinct Characteristics of Science

Science is the most successful method that has ever been employed for the understanding of the physical world; knowledge obtained by science can in most cases be tested and can thus be validated. There is only one science and the knowledge it provides is society's heritage of common knowledge. As such it transcends national boundaries and generations. It belongs to all humanity; generation upon generation builds on all of humanity's prior scientific accomplishments. Although today most of the scientific research is still done, and most of the profit from the latest advances in science is still concentrated, in the developed nations of North America, Europe, and Asia, scientific knowledge is, in principle, available to everyone; modern communication systems have made this possible. The heritage of common knowledge provided by science is a unifying force for humanity.

Embedded in the tradition and method of science are distinct characteristics of science which qualify many of its functions. These characteristics need to be recognized and adhered to if science is to serve well and in a balanced way both itself and society.

*Science is a self-correcting system* Science is cooperative and at the same time encourages originality, independence and dissent. It stresses the need for an open mind; time and again the scientist must reverse direction, and he normally does. Proven scientific positions proved wrong no matter how great. Interpretations of experimental data and observations, explanations of events, and paradigms of theories have had alternative rationalizations and have always been limited, never complete. This helps the scientist tolerate ambiguity, strive for improvement, and allow for error and self-correction.

*Science teaches the value of relatedness and embeddedness* A necessary condition of all life is interdependence; everything relates to everything else; nothing exists in isolation. Hence everything assumes essence via its interactions with the something else. Science, therefore, seeks not only truth, but also relatedness and embeddedness within its domain. One branch of science relates to and in varied degrees is embedded in another. Out of this implicit coupling of the parts of science emerges the underlined unity among its seemingly chaotic functions. The mutual embeddedness of the parts of science allows for their integration, feedback, and accommodation (e.g., embeddedness of physics in chemistry, biology and technology and vice versa). Each branch of science, especially the neighboring ones, cross-fertilizes the others; they draw from, reinforce, and are indebted to each other. This process is continuous and accounts for the unceasing readjustment of the functions of science within and between its parts and the ultimate cohesiveness and advancement of science as a unified whole.

*Science is changing, it is becoming more complex* The growth of modern science is becoming increasingly more complex. How will this affect its future efficiency, stability and resilience? Will science get so complex that it will collapse like other things do when they have no other way but to keep growing and to keep becoming more complex, or will science advance independently of its size and complexity? Clearly, this would depend on its practitioners and the users of scientific knowledge, but it would also depend on the big politics of science, science's big sponsors, and on how society perceives science and its impact. Large international projects like the Intergovernmental Panel on Climate Change, the human genome, the International Thermonuclear Experimental Reactor, the European Organization for Nuclear Research, the large "user" facilities (e.g., particle accelerators), the big data facilities for medicine, and the knowledge being generated in cyber space, are but examples of this trend. Even the character and culture of today's large-scale research at major research facilities has been changing.[38]

Changes in the production of scientific knowledge, including the growth of "hybrid" public-private sponsorships raise concerns about the independence and impartiality of science. Similar-type concerns are raised by changes in the way science and science-based technology are governed and operated, particularly because of globalization and the sheer size of some of these activities. The earliest and possibly strongest concern has been the "Military-Industrial-University Complex". It has since been joined by other "complexes" such as "The Medical-Industrial Complex",[39] which is seen to be increasingly shifting research done by universities to companies. The shifting of activity in biomedical science toward the big projects and the big companies continues unabated.[40] For instance, genomics is driving megamergers as companies seek to lock in patents and licensing agreements, and so do agrocompanies. Many worry that this shift will further erode science's independence and impartiality.[41]

Clearly, a fundamental change is seen in the functioning of science showing that the future of science rests not only with its practitioners but perhaps more so with its sponsors and its users.

A most distinct characteristic of science is its universality which is discussed in the next Section.

## 3.6 The Universality of Science

Science is universal in at least two fundamental ways: First, regarding the applicability and validity of its method, the generality of the physical law, and the effects of scientific knowledge on human functions and wellbeing. Second, regarding the participation of humankind in it; science's growth is rooted in the discoveries of all nations, and the knowledge it provides is (or can be) universally-shared. A prerequisite for the universality of science is freedom of work and communication in science, wisdom and caution in the application of scientific knowledge, and opportunity for every nation and every generation to participate in, and profit from, scientific discovery. This way, the heritage of common knowledge provided by science becomes a unifying force of humanity and a source of universal hope. Meaningful participation in a broader effort and sharing in the common accomplishments instills pride in the individual *whether* in science or in other walks of life. Through the knowledge science provides, science-based technology brakes up the isolation of totalitarian states, liberates oppressed peoples, and exposes human suffering. Indeed, science has made the panoply of totalitarian and dictatorial regimes obsolete by enabling its penetration from within and from outside. Science is, thus, looked upon as a liberating force for humankind (see endnote 1).

The universality of science has been defined by several scientific organizations. For instance, for the International Union of Pure and Applied Physics (IUPAP) the universality of science "entails the free circulation of scientists, the freedom to communicate among scientists and to disseminate scientific information", and for the International Council for Science (ICSU) it entails the "freedom of association, expression, information, communication and movement in connection with international scientific activities". These scientific freedoms should be coupled to responsibilities.

The aforementioned definitions do not seem to be broad enough. As I have indicated earlier (see endnote 13), the definition of the universality of science needs to be broadened to include the *universal acceptance of science by society*; in those lectures (see endnote 13), I have outlined some of the limits to and some of the needs for the universality of science. I had expressed the view that while the recent advancement of science has been spectacular and the scientific frontier endless, the universal acceptance of science by society is still limited and is still in need of a more effective transmission of the intellectual and cultural value of science. A large fraction of society looks at science with fear and suspicion and views a science-dominated world as unbalanced. A good fraction of society also fears science's impact on man and believes that science has "set its own conditions and imposes its own values" on society.[42] In Vaclav Havel's view, "modern science describes a single dimension of reality…. and the fewer answers the era of rational knowledge provides to the basic questions of human being, the more deeply it would seem that people, behind its back, cling to the ancient certainties of their tribe".[43] A view not unlike the harsher one of Jacques Maritain, claiming that the "deadly disease" science set off in society is "the denial of eternal truth and absolute values".[44] Such views restrict science.

### 3.6.1 Limits to the Universality of Science

I have elaborated earlier (see endnote 13) on the limits to the universality of science and identified six areas which limit science's universality. In this Section reference is made to these limits, which are further expanded.

*First Limit: The preponderance of humanity is still not participating in the advancement of science and does not share the fruits of scientific knowledge.*

Although today science transcends locality, it still bears the imprint of locality; and although we scientists demand freedom, we often forgo responsibility.

Most of the scientific research today is done by the developed nations of North America, Europe, and Asia. About 95% of the world's Research and Development (R&D) is conducted by the 20% of the technically advanced peoples. Despite recent progress, neither the scientific knowledge nor the scientific technology is available to most of the world. Most developing countries are practically with little or no science. According to a recent report by the InterAcademy Council (IAC)[45] most industrialized countries are devoting between 1.5% and 3.5% of their Gross Domestic Product to R&D and in fact many have pledged to increase these investments.[46] This great expansion of R&D has altered the global distribution of science and engineering. According to a US National Science Board report,[47] world-wide R&D expenditure rose from $522 billion in 1996 to $1.3 trillion in 2009; interestingly, also, while in 1999, 38% of the world's R&D was performed in the USA, 27% in Europe and 24% in Asia, in 2009 Asia accounted for 32% of world-wide R&D, the USA 31%, and Europe 23%.

In today's world, the scientific and technological isolation of most of humanity is not acceptable. Without proper access to scientific literature and technical information, and without adequate means and materials needed for their indigenous science and technology, *developing nations will continue to remind us of the limits of the universality of science.*

The universality of science requires willingness to find the means and to devise procedures that will allow sharing of scientific knowledge. Indeed, how can we call for a *"knowledge society"* and still restrict direct access to scientific literature for a large part of humanity? ***ALL scientific publications should be made public at the instant of publication.*** Scientific literature should be regarded humanity's property, and access to it should be unconditionally free of charge. It is encouraging that recently it is generally acknowledged that the denial of access to a substantial part of the scientific literature without subscription constitutes a serious impediment to the advancement of science. Progress is thus being made.

*Second limit: The "limitless power" of the method of science.*

While the ability of science to answer questions which can be defined scientifically is practically limitless, *the impression that there is no limit to what science can do, limits the universality of science,* because there are limits even within the borders of science. As it has been pointed out repeatedly in this book, the reductionist approach of physical science cannot explain the properties of living matter; it is hindered by the enormous differences in the scale of complexity and by holistic properties and teleology issues. Live organisms may have their own laws, which, while not in opposition to the known laws of physics, cannot be reduced to them, because the understanding of living organisms is not possible with only the knowledge of the atoms and the molecules that constitute them. Neither it is possible to comprehend the basic phenomena of life based on the known laws of physics, nor it is possible to understand man only by a reductionist's view of him.

There are still other limits at the boundaries of science. There are, for instance, questions which although defined scientifically, have no scientific answers when formulated because they lie outside the province of science (see Chap. 6); questions such as "What is the origin of the universe?"; "What is the origin of life?"; "How did the first organism emerge from inorganic matter?"; "If matter evolved according to the laws and the forces of Nature, what is the origin of those laws and those forces?". These are questions that science can ask, but science cannot answer (at least for now). Scientists can express opinions about such questions, but they cannot provide scientific answers. Questions of this kind show that although the borders of scientific knowledge are continuously expanding, some questions remain; they belong to the area of "trans-science" (see endnote 1).[48] *The pretension that we have scientific answers for such questions, limits the trustworthiness of science and its universality.*

*Third limit: The real or perceived adverse impact of science on traditional values; fears that the scientific view diminishes man.*

Values lay deep in humanity's multiple cultures, traditions and religions. Traditional values – such as respect for life, liberty and justice; commitment to peace, freedom, and human dignity; reciprocity – are mutually embedded and mutually indebted; they guide human behaviour and constitute the frames of reference for value judgment (see Chap. 5).

Science per se does not deal with values. Science, however, is not value-free in the execution of scientific research and in the application of scientific knowledge. There are values ***in*** science and there are values ***of*** science. The search for truth in science imposes on the researcher a moral conduct, which is not unlike the moral conduct of a person in the broader society, but it goes further. Science confronts the work of a scientist with the work of his colleagues and cannot survive without justice, honour and respect among them. Science, furthermore, is based on the free communication among scientists and on mutual trust. Freedom of thought and speech, justice, dignity, self-respect, and tolerance of differing views are all values recognized in the past – long before modern science – as necessary for the survival and wellbeing of society. Science relies on these very values for its functioning because scientific research is conducted by and for people; because science itself is first and foremost a human activity. Thus, while the scientific picture of the world changes continuously, the values on which science and scientific behaviour are based remain fundamentally the same: universal, timeless values.

There are as well, the values **of** science, which characterize its functioning: rationality, verification of knowledge, discovery and correction of error, respect for and acceptance of the proven fact, unification and coherence of scientific knowledge, cooperation, humanism. Humanism is a uniquely multidimensional value of science; as I wrote elsewhere (see endnote 1), "If deep in the essence of civilization lies the emancipation of humanity, society cannot be truly civilized without science". These values of science need to be broadly appreciated and to be recognized as complementary to the traditional human values. This recognition and this complementarity are necessary to moderate the image of modern scientist as antagonistic to accepted beliefs, norms, and values, and as increasingly questioning the traditional foundation of Western Civilization. *The degree to which the scientists and society are successful in this endeavour will enhance or limit the broader acceptance of science by and for the benefit of society, and thus the universality of science.*

The scientist, furthermore, is faced with the deep-rooted fear of society that the scientific view of life diminishes man. To the Greek philosopher Protagoras "*Man is the measure of all things*" and to Aristotle "*Man is the ultimate supreme creation in the cosmos*", while to Christianity "*Man is the image of God.*" Today, many fear that science is making this traditional Western-Civilization-View of man obsolete. Many across society believe that science "has set its own conditions and imposes its own values" on society, others warn that "society (is) dehumanizing rapidly," while still others claim that we are heading for "scientific control of society" (see endnotes 42, 43).[49,50,51,52] Independently of the validity of such claims, *the view from science, as presented by most scientists, clashes with the view upheld by a large fraction of society that man is the supreme value par excellence.*

And one can go even further, the fear of many in society of the possible effects on man of the recent scientific developments in biomedical sciences. They point to the ethics of human genetic engineering and to the possibility of inheritable genetic modifications in humans and thus they fear that humans are to be turned into and be bred like animals, hence signalling the end of man (see endnote 52). Independently of the validity and the extent of those fears, it is evident that t*he downfall of man unavoidably means the downfall of science.*

*Fourth limit: Issues beyond the province of science.*

Science is not the only way to the truth, and to claim otherwise, as many scientists do, is a distortion of science leading to conflict. The world is a hybrid of many things, and there are other, complementary, ways to the truth besides science such as those of art, philosophy and faith. Science deals with questions that can be defined scientifically, that can be studied scientifically, and that can have a chance to be answered scientifically; and scientists should demand respect by society of the proven scientific facts. However, science deals with neither ethical judgments, nor with the ultimate meaning of life. There are neither ontological experiments in science nor laws which describe our love and respect for each other. Those lay outside the province of science.

Beyond science, beyond the physical and the biological, beyond that which can be proved by the method of science and can be measured by the scientific instruments, lay the spiritual, the cultural and the intellectual traditions, the values of man, and the teleological concepts of philosophy and religion of which science does not speak. *To dismiss those "non-physical" aspects of human reality because they are not "proved" by the method of science, or to abandon science's metaphysical neutrality and transform science to a myth, limits the universal acceptance of science by society and presents the scientist antagonistic to traditional world-views.*

The general acceptability of science is largely because science makes no metaphysical claims. When that premise is abandoned, science will be judged differently and science will face a more confrontational society. *This will limit science's universality*.

*Fifth limit: Perception of science as power to suppress and to destruct, and perception of scientists as instruments for negative use of scientific knowledge*.

It is not possible to separate science from the consequences of the negative impact of the application of scientific knowledge. Increasingly, more people in society point to the dark side of the applications of science and picture science as a source of dangerous knowledge, which is used for destruction and limitation of man's freedom, safety and privacy. "The frightening thing which we did learn during the course of the war (WWII)", said I. Rabi "was how easy it is to kill people when you turn your mind to it. When you turn the resources of modern science to the problem of killing people, you realize how vulnerable they really are".[53,54] Science is thus looked at by a fraction of society as having set loose against society unimaginable forces capable of causing widespread destruction and suffering, be it through nuclear weapons, chemical agents, or biomaterials. Look, they say, at the dimensions of the nuclear arsenals (Table 3.1).[55] Today, the nine known nuclear powers have collectively over 20,000 nuclear warheads ready for immediate deployment; each of the thermonuclear bombs in these arsenals has a typical explosive power of several megatons. And they go further, they point out that the cataclysmic consequences of these weapons are with us because science and the scientists made it so. Because, since WWII, the frontiers of science and technology have become the frontiers of weaponry. Many of these weapons, including nuclear weapons, have been recommended, invented, developed and perfected by scientists and engineers, in the beginning and since. *The fear that science is increasingly becoming a power*

**Table 3.1** The nuclear arsenal of the nine (9) countries known to have nuclear weapons[a]

| Country | Date of first explosion | *Estimated* number of warheads |
|---|---|---|
| USA | 1945 | 5400 |
| Russia | 1949 (USSR) | 14,000 |
| UK | 1952 | 185 |
| France | 1960 | <350 |
| PRC | 1964 | <160 |
| India | 1974 | 100–140 |
| Israel | 1979? | 100–200 |
| Pakistan | 1998 | 60 |
| North Korea | 2006 | 0–10 |

[a]Based on figures given by R. S. Norris and colleagues in several articles in the Bulletin of Atomic Scientists (see endnote 55); Also, see Reference 1 and S. Fetter et al., Physics Today, April 2018, pp. 33–39.

*for suppression and destruction, and the perception of scientists as instruments of war diminishes their positive image and clouds their benevolent arguments.*

Scientists have always had some part in military engineering (see endnote 1).[56] However, never before has so large a part of science been employed in this way than recently. It is estimated[57] that about half of the scientists and engineers in the USA and the world today are employed in the military field, many devising bigger and better weapons, weapons delivery systems, laser-guided bombs, military communications, as well as new nerve gases, germ warfare, so on. Science and scientists are unquestionably responsible for the dangerous nature of modern weapons – without modern science such weapons would not have been possible. The most horrifying possibility of modern war is of course nuclear war. Many scholars agree that the two superpowers have stockpiled enough nuclear weapons to destroy human life, and much of the rest as well*, many times over*. And alas! nuclear weapons technology is proliferating; new countries are engaged in efforts to acquire nuclear weapons[58] as we face another existential challenge, this time from bioscience.[59] What a distortion of science!

Interestingly, a 2011 editorial in *Nature* magazine[60] writes: "Twenty years after the end of the cold war, scientists and the military still need each other…. The US defense complex is the world's largest investor in military research. Much of the money has gone into developing weapons of unprecedented lethality, but large fraction supports 'dual-use' research, whose products – from the Internet to the Global Positioning System – have enriched society as a whole."

The atom bomb was the invention of scientists; they began the work on the atom bomb at their own volition. It is not usually the job of university professors to work on weapons of mass destruction, many have noted. Why then did these scientists initiate such work? Fear, they say, that the scientists of the other side could develop the bomb first and use it. And yet the nuclear bomb led to the nuclear power reactor, exemplifying the dangerous connection, **atoms for peace via atoms for war!** *There is thus a pressing need for radical scientific change, a need for a paradigm shift in the functions of modern scientists. Science will be severely limited, unless its power to suppress and to destruct, and to use scientists in this process, is curbed.*

*Sixth limit: The careless scientist; scientists beyond the borders of science.*

*S*cientists often step over the scientific norms, step over the borders of science, and become antagonistic in matters not scientific.[61] They speak on behalf of science on non-scientific matters or even on trans-scientific questions, spreading criticism, for instance, to the realm of religious belief, based not on what science says but rather on personal philosophy and personal world view. Geneticists tell us that they have discovered "The Language of God," theoretical physicists that they have discovered "The God Particle," astrophysicists that they have discovered "The Mind of God" and that their theory now says God does not exist ("God is unnecessary"), evolutionary biologists that they have discovered "The Selfish Gene" and the "God Gene" and still others that they have discovered the "Theory of Everything". Such expressions, even if they are not taken seriously, give the erroneous impression that science is omnipotent.

It is exceedingly disturbing to see scientists deal with God *scientifically!* To deify scientific theories is to turn science into a myth and expose science to undue criticism. Many in society are genuinely concerned that science is being turned into scientism and scientists into the High Priests of a new world view aiming to replace traditional world-views.

We need to adhere to the scientific tradition and to confine ourselves to questions which science can answer. We need to observe the proper boundaries of science. And we need to distinguish when we are doing science and when we are extrapolating from it*, especially when we are teaching students.*

Equally discomforting is the fact that scientists frequently abdicate their responsibility to the norms of science in favour of national and commercial interests. As the percentage of scientists who work for governments and industries increases, problems of freedom of inquiry and communication increase.

Even more troubling are the reported increased incidents of fraud in science,[62,63] suggesting that serious breaches of ethical behavior in scientific research are on the rise.[64] Typical serious breaches of ethical behavior that have appeared recently include those in South Korea[65] and those at premier USA Universities and Research Centers (Berkeley, Columbia, Harvard, Yale, Bell Labs, MIT).[66,67,68,69] Such behavior clearly weakens the bonds between science and society and lowers the trust of the scientist by society. Establishing the validity of each new scientific result is essential, for there is no scientist who did not err and because there have been examples of scientists who believed their results were valid but they were not (e.g., cold fusion[70,71]). There are also honest mistakes which are subsequently corrected and the respective original publication retracted. Such is the recent case involving a group of scientists at CERN in Italy, who in 2011 reported an experimental finding that neutrinos had traveled faster than the speed of light.[72,73] If confirmed, this result would have disproved Einstein's 1905 Special Theory of Relativity and would have contradicted more than a century of physics research based on the assumption that nothing exceeds the speed of light in vacuum. In making the announcement the leader of the research group urged caution, stating that the group had tried and failed to find a mistake in the research and that it was up to the scientific community to examine and replicate the work. The announcement was widely publicized. Subsequently, in 2012, experiments performed by a different group at the same laboratory found that neutrinos travel at the same speed as light. This is a sad story of honest research, which has been corrected through subsequent work. The story, however, raises questions as to when and how research groups and institutions should announce or publicize results that would be considered revolutionary or anomalous. Situations such as these differ from those where scientists were wrong and it has become clear that the scientists involved knew their results were fraudulent.

There is still much to be desired as well, in answering the cynical criticism levelled against us, namely, that "in the end, most scientists will do whatever there is money for doing." Regrettably, this has been shown to be the case time and again since Daedalus in ancient Greece.

There is, thus, a need to tame the arrogant and irresponsible scientist and to uphold the scientific values and tradition of an open-mind, modesty, honesty, and tolerance, and to improve our image. *The diminution of respect for and trust of the scientist by society limits the acceptance of science by society.*

What, then, can history tell us about the future of the "scientific" civilization? Clearly, any civilization's survival depends on its ability to adjust to change, to adapt. Science has no problem with that. Throughout history, civilizations have risen, reigned and fallen. For how long then might the scientific civilization continue to rise and reign, and when might it be expected to decline and ultimately collapse? The rise and reign of a civilization, it has been argued,[74] depend on its effective transmission to future generations, and one of the obstacles to this transmission is the subjective nature of its criteria. Science's "objectivity" must then be closely guarded if the scientific culture is to be effectively transmitted to future generations.

The universality of science requires coherent integration of science and its values into the world culture and this cannot be done through fear or scorn, or material promise, or through biological modification and manipulation of *Homo sapiens.*

### *3.6.2 Needs of the Universality of Science*

For science to become truly universal:

- The trust of society in science and the scientist must be safeguarded and indeed it must be enhanced; the most significant factor in effecting this goal is the responsibility of the scientist.
- The scientific culture and the humanism inherent in science need to be more effectively communicated to society.
- The scientists should address the fears and concerns of society with modesty and must respect the dignity of man.
- The values of science and the traditional values of society need to achieve mutual accommodation.
- Science needs to work with society to address the ferocious problems facing humanity today – such as those of war and peace, deterioration of the environment, climatic change, and world poverty – for which a strong science is necessary but is not sufficient.
- Science must reassess its deep involvement with the machinery of war.

## 3.7 Science and Society

### *3.7.1 The Scientist*

The crucial element of science has been and still is the scientist. Who is he? I attempted to answer this question in a book I published in 2001 and noted then, that today neither science is as distinct a term as it once was, nor is there distinctiveness in the term scientist. The proliferation in the numbers of those working in science today, the expansion of the scientific endeavor, and the vast uses and applications of scientific knowledge has resulted in more than one scientific identity. Today, the term scientist embraces many and diverse people with broad and heterogeneous areas of expertise, interests, attitudes, and values. In science, today, there are many science workers and relatively fewer scientists, and while both are indispensable elements of science, the heart of science remains the scientist.

Historically, scientists formed a community with no boundaries, where, in principle, everyone is free to enter, to work, to express his or her views, to be heard and to be contradicted. They adhered to the values inherent in the practice of science. Their community, though highly competitive, has traditionally been rather stable and largely incorruptible, sustained by a sense of dignity for its members. The scientific community itself has been largely shielded from social and metaphysical controversy by its limited impact on society, especially on man, and by metaphysical neutrality. Today, this is so no more. Hence the question: will the scientific community continue its stability and adherence to its tradition and norms so necessary for the benefit of both science and society?

Today, many young people seem not to be attracted by the challenges of a scientific career; many drift to easily-get-rich jobs rather than take the difficult road of becoming a scientist. The distinct characteristics and principles of science which are embedded in its tradition and method of inquiry need to be recognized and adhered to by the young scientists; they are normally learned tacitly in the execution of research and the proper guidance of the mentor-professor. There seems to be a need to broaden a scientist's education and societal perspective for there are difficult questions which are more frequently being asked today than in years past. Questions such as, could there be scientific knowledge the possession of which is harmful to society and thus further accumulation of such knowledge inappropriate? Is the primacy of unhindered right to new knowledge absolute, or should it be moderated by the legitimate concerns of society? *Whatever the answers to these and to other related questions might be, it is certain that man, as scientist and as citizen, will be increasingly limited by the burden of responsibility the power of scientific knowledge imposes on him.*[75]

## 3.7.2 Scientist and Society

### 3.7.2.1 Mutual Responsibility

Citizens of many countries around the world have different attitudes toward science and the scientists. Many citizens continue to hold scientists in high regard, while others mistrust them and at the same time expect miracles from them. It is the mutual responsibility of scientists and society to achieve a better understanding.

While today more countries invest in science and science education than previously, there is still a need to increase the science literacy of the citizen.[76] It is essential for society to recognize that virtually every major issue confronting society has a science and technology component requiring public understanding. It is also of utmost importance for society to appreciate the value of freedom in the execution of scientific research and the necessity to secure conditions conducive to scientific freedom. Only in a completely open society can the integrity of science be maintained and the dark side of science diminished. It is thus,

- The mutual responsibility of scientists and society to curb the power of science to suppress and destruct and to deploy scientists in this process. There is a need for radical change in this regard, a need for a paradigm shift in the functions of modern scientists. Science needs to reassess its deep involvement with the machinery of war.
- The mutual responsibility of scientists and society to predict, prevent and manage the risk against the idea of man associated with the progress of science. There will be immense future challenges to science and to human values arising from the impact of science and scientific technology on man.
- The mutual responsibility of scientists and society to require that the application of scientific knowledge is compatible with the values of society. For this, scientists and society must achieve accommodation between their mutual value systems and enhance their mutual trust. Obviously, the ethics of modern man cannot be based on science, but neither can it be separated from it, nor can science claim to be amoral.

#### 3.7.2.2 Needs of Scientists and Society

Society needs to be more open and willing to embrace the acceptance of science. Society still fails to fully appreciate what science is providing for it despite the benefits it derives from science and although modern society will cease functioning without science and science-based technology. All too often society takes the benefits of scientific discovery for granted and all too often society exaggerates out of fear or ignorance potential negative impact and risk of new scientific knowledge. *Society, therefore, needs to accommodate science's unique ways of functioning and adjust to the facts of new scientific discovery, fully cognisant that scientific knowledge comes with benefits, but also with "peril and pain".*

Repeatedly in the recent past the relationship between the scientists and society has been strained by several key issues – embryonic stem cell research and climate change to name just two. In such instances, society is not just sensitive to what science does or does not do, but oftentimes society overreacts casting aside long-range benefits. The recent reaction regarding scientific data used to evaluate climate change[77] makes the point and may suggest that the trust between science and society is rather fragile. *An important aspect of the scientific literacy of society then should be enhancement in society's ability to recognize that while even in science errors are made, inherent in the method of science is the capability to discover and to correct such errors.*

Only in a free and open society can the integrity of science be maintained, and a free and open society is foremost society's responsibility.

### 3.7.3 The Scientist as Policy Advisor and as Advocate

Science advisors have been around for a very long time. One might in fact argue that the first scientific advisor in human history was Aristotle: he was the advisor of Alexander the Great. However, the emergence of scientists as political advisors, peacemakers and diplomats is a recent phenomenon, largely a product of the role played by scientists in WWII activities.

Today, enormous new scientific knowledge is generated across all fields of science, which is significant for human wellbeing; this powerful scientific knowledge is easily accessible and can quickly be put into practical use. Thus, the view is prevalent that scientists have a responsibility to advise governments, decision makers, and the public, of the possible benefits and risks of new scientific knowledge and science-based technology and to help them choose wisely between available options. There is a need to develop ways for "Science for Policy" activities, which will make possible the input of scientific evidence into the decision-making process and aid the resolution of social issues, claims and conflicts. Such an engagement of the scientist requires deep knowledge of the specific scientific issue and a holistic rather than a reductionist approach in translating scientific evidence into public policy; accountability in public policy, many have said, requires scientific evidence to be correctly embedded into the democratic process. The most important criteria for a scientist's contribution in this capacity are scientific competence, integrity, independence and transparency. These are basic prerequisites for an impartial assessment of the facts of science pertaining to the issue at hand worthy of the trust of society. To examine the impacts of policy decisions and to help mitigate their risks it is necessary to base such decisions both on science and on the values of society, to situate scientific evidence in the context of society's value system, and political judgments to be evidence-based. The subject has been discussed extensively for some time and a recent account can be found in Reference[78].

"Science for Policy" is needed to:

- *Aid society and decision makers in crises with scientific dimensions*. Examples of such crises are the Severe Acute Respiratory Syndrome (SARS) and other epidemics, the Fukushima nuclear accident, and earthquakes, tsunamis, hurricanes, floods, volcanic ash clouds, terrorism, and so on.
- *Clarify scientific claims on important controversial scientific-technological issues where answers are still not clear and claims are still not fully trusted.* Using the EU as an example, one can cite several science policy controversies of this kind: climate change, GM crops, fracking, food safety and security, water security, and a series of environmental and energy issues. And there are still science and technology relevant issues which may transcend the technical knowledge needed to provide a complete resolution of the issue, but scientific advice is

nonetheless sought to help the decision-making process even before a complete scientific understanding is reached. For instance, the possible effects of electromagnetic radiation on human health; although several major studies[79,80] have found that the use of mobile phones and exposure to radiation from high-voltage transmission lines does not pose any health risks, public concern about radiation from mobile phones and high-voltage transmission lines continues.

- *Delineate proposed claims for or against a given issue*. Invariably, risks arise when businesses or interest groups interpret scientific facts beyond the truth they contain. Often even honest science is mistrusted because of where it gets its funding. It is argued as well that even in countries where free speech is the norm, institutions are not always as open as necessary to dissenting voices. Impact assessments prepared to accompany policy proposals may, for example, be deliberately limited in the options they considered and in the sources of data they used, with the aim of achieving a desired outcome. Lack of openness in evidence gathering oftentimes has resulted in impact assessments being focused more on risks than on opportunities, in being more cautionary.
- *Choose wisely the mechanisms from which advice is gotten.* Today, it seems everyone wants to have scientific advice (especially the government) and everyone wants to give scientific advice, foremost to the government! Thus, debates over structures and procedures necessary for sound scientific advice abound. Unquestionably, society needs broad-based, open, evidence-gathering mechanisms to act. Four structures commonly used are: *individual scientists, chief scientific advisors, advisory councils/advisory committees, National Academies and Academy Organizations.* There has actually been a proliferation of Academy Organizations [International Council for Science (ICSU), InterAcademy Partnership (IAP), InterAcademy Medical Panel (IAMP), Federation of European Academies of Medicine (FEAM), European Academies Science Advisory Council (EASAC), All European Academies (ALLEA), European Council of Applied Sciences, Technology and Engineering (Euro-CASE), Academia Europaea (AE), and others][81] offering "independent" and "competent" scientific advice to governments and national and international organizations, "which often moderates extreme views on key issues and balances advocacy". National, regional, and global Science Advice Mechanisms are necessary for expert, competent and conditionally- and-contextually-independent advice.
- *Delineate the role of the scientist as a policy advisor and as an advocate.* The views of scientists (whether acting alone or as members of academies/organizations/committees) are respected because they are supposed to be objective and independent experts in the field advice is sought, but when they act as advocates they are likely to be in conflict with the professional norms of science. Advocacy by the scientists themselves on behalf of any issue be it the environment, global warming, shale gas extraction, GMFs, stem cells, or synthetic biology, may be a real or perceived attempt to affect the opinions of the general public or certain groups of population, or the decision making of politicians, legislators and governments. It is obviously not just risky but unfair to assume that when scientists become advocates they become partisans and are no longer "neutral conveyors of scientific information". Yet, scientific advice almost always contains shades of

opinion not entirely scientific, and the goals and methods of advocacy can be in conflict with the goals and methods of science. It is not uncommon to find the experts whose advice is sought to be the ones with vested interests in the subject they are called upon to give advice. Thus, the advice should be sought more broadly and should include competent people from outside the subject matter concerned. Does everything that scientists say or advocate have the backing of science and is self-regulation of scientists adequate to handle the pressures placed upon their scientific integrity? While potential sources of conflict will always accompany science advising, one aspect is clear: *support good, evidence-based policy, and clarify the boundaries and validity of the information provided.*

Undoubtedly, we are witnessing new paradigm shifts as to the role of scientists and their scientific societies.

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38. See, for instance, R. P. Crease and C. Westfall, Physics Today, May 2016, pp. 30–36.
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40. Attention is also being drawn to the megatrends (large economic units such as Google and Apple) seen in the Silicon Valley “that exercise a form of sovereignty of their own” (Sidney D. Drell & George P. Shultz (Eds.), *Andrei Sakharov—The Conscience of Humanity*, Hoover Institution Press, Stanford University, Stanford, California 2015, p. 135).
41. Another area of concern is the relationship between security and science and the difficulty in balancing scientific freedom and national security concerns. Kraemer and Gostin (John D. Kraemer and Lawrence O. Gostin, *The Limits of Government Regulation of Science*, Science **335**, 2 March 2012, pp. 1047–1049) focused on this issue referring to the case of genetically modified H5N1 avian influenza viruses. They write that the US National Science Advisory Board for Biosecurity, “recommended that two journals, Science and Nature, retract key information before publication”, because of “concerns that published details about the paper’s methodology and results could become a blueprint for bioterrorism”. Researchers want no restriction and access, no

government intrusion.… "However, security advocates believe the greater risk is that mutated virus could escape or that knowledge about these mutations could get into the wrong hands. They suggest that research of this kind should not be funded or undertaken in the first place."
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50. Loucas G. Christophorou and George Contopoulos (Eds.), *Universal Values*, Academy of Athens, Athens 2004 (ISBN: 960-404-061-8).
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52. See, for instance, Leon R. Kass, *Life, Liberty and the Defence of Dignity—The Challenge for Bioethics*, Encounter Books, San Francisco 2002; Gregory Stock, *Redesigning Humans—Choosing our Genes, Changing our Future*, Houghton Mifflin Company, Boston 2003; C. S. Lewis, *The Abolition of Man*, Harper, San Francisco 2001.
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54. Increasingly society considers that scientists have a moral responsibility to answer for what they do in their research. For instance, no experiments can be defended aiming to determine the most economical and best engineered way to carry out the mass destruction of people.
55. R. S. Norris and collaborators in the Bulletin of Atomic Scientists 2002, 2005–2008 (see also References 1 and 9).
56. Classic examples of military engineers are Archimedes, Leonardo da Vinci and Michelangelo. It should be noted that Abraham Lincoln established the US National Academy of Sciences during the Civil War in part to provide advice on military matters.

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59. L. F. Cavalieri (The Bulletin of the Atomic Scientists, December 1982, p. 72) writes: "There is a striking similarity between nuclear science and genetic engineering. Both major accomplishments confer a power on humans for which they are psychologically and morally unprepared."
60. Editorials, Nature **477**, 22 September 2011, p. 369.
61. See, for instance, Jian Hilgevoord (Ed.), *Physics and our View of the World*, Cambridge University Press 1994; M. Ruse, *Is Evolution a Secular Religion?* Science **299**, 7 March 2003, p. 1523; Michael Ruse, *The Evolution-Creation Struggle*, Harvard University Press, Cambridge, Massachusetts 2005; Richard Dawkins, *The God Delusion*, Houghton Mifflin, Boston 2006; Elaine Howard Ecklund, *Science vs. Religion—What Scientists Really Think*, Oxford University Press, New York 2010.
62. Adil E. Shamoo and David B. Resnik, *Responsible Conduct of Research*, Oxford University Press, New York, 2003.
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75. A recent Interacademy partnership report (Interacademy partnership, *Doing Global Science*, Princeton University Press, Princeton 2016) expresses concerns about the increase incidents of misconduct in research; it states: "irresponsible behavior and poor practices pose threads to the global research enterprise, could impair its effective functioning, and could even damage the

broader credibility of science." A similar publication by ICSU in 2008 provided "guidance about the responsibilities and freedoms of researchers", and in 2009, NAS-NAE-IOM (The US National Academies of Sciences, Engineering and Medicine) issued an educational guide "*On Being a Scientist: A Guide to Responsible Contact of Research*". In 2012 a publication by the InterAcademy Council (IAC) and the IAP (the Global Network of Science Academies) entitled *Responsible Conduct in Global Research Enterprise: A Policy Report*, describes the values of research and how those values should guide the conduct of research. The report acknowledges that "while different disciplines and countries have varying research traditions and cultures, the fundamental values of research transcend disciplinary and national boundaries and form the basis for principles of conduct that govern all research". In March 2017, ALLEA issued a revised edition of its earlier document entitled "*The European Code of Conduct for Research Integrity*".

76. Rendiconti Lincei, Vol. **23**, Supplement 1, *Science Literacy*, September 2012.
77. See comments by Martin Rees and Jane Lubchenco in Science **327**, 26 March 2010, pp. 1591–1592. See, also, R. J. Cicerone, editorial, Science **327**, 5 February 2010, p. 624; Eli Kintisch, Science **327**, 26 February 2010, p. 1070.
78. James Wilsdon and Robert Doubleday (Eds.), *Need Foresight for Scientific Advice in Europe*, Centre for Science and Policy, April 2015, Cambridge (ISBN: 978-0-9932818-0-8).
79. NIEHS Working Group Report, *Assessment of Health Effects from the Exposure to Power-Line Frequency Electric and Magnetic Fields*, National Institute of Environmental Health Sciences of the National Institutes of Health, US NIH Publication No. 98-3981, August 1998; for subsequent articles and reports on this subject see British Journal of Cancer, American Journal of Epidemiology, and Epidemiology.
80. On the question of mobile phone radiation and health, articles can be found in the journal of Health Physics, Journal of Exposure Analysis and Environmental Epidemiology, Occupational and Environmental Medicine, American Journal of Epidemiology and the British Medical Journal. See also http://en.wikipedia.org/wiki/Mobile_phone_radiation_and_health.
81. Actually, since 2016, five European Academy Organizations—Academia Europaea, ALLEA, EASAC, FEAM and Euro-CASE—are working together under the name SAPEA (Science Advice for Policy by the European Academies) to provide as a group "interdisciplinary evidence-based advice, reviews and other scientific input to the Science Advice Mechanism (SAM) of the European Commission".