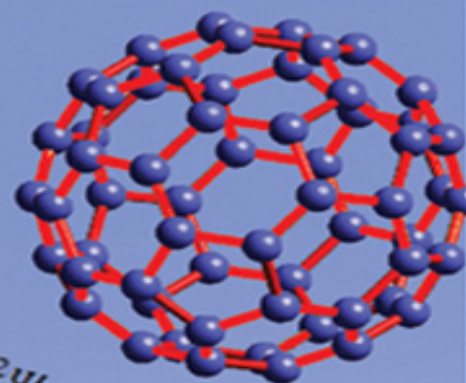
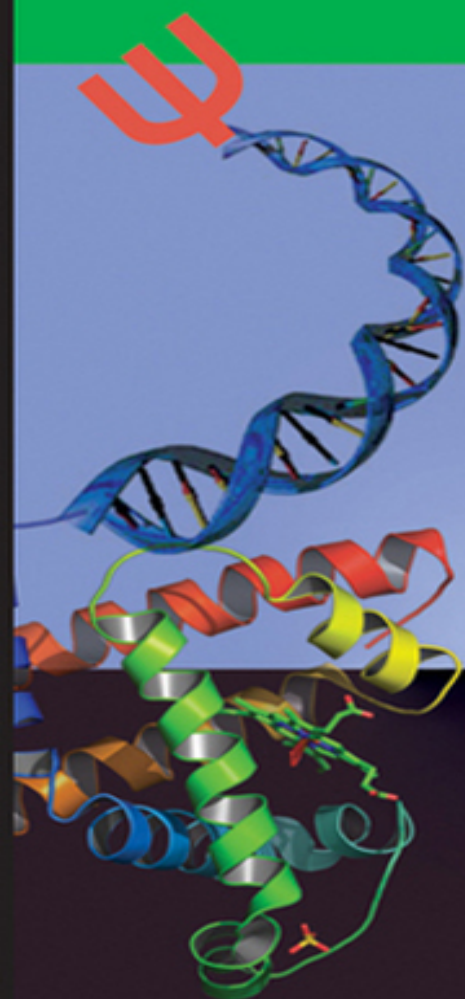




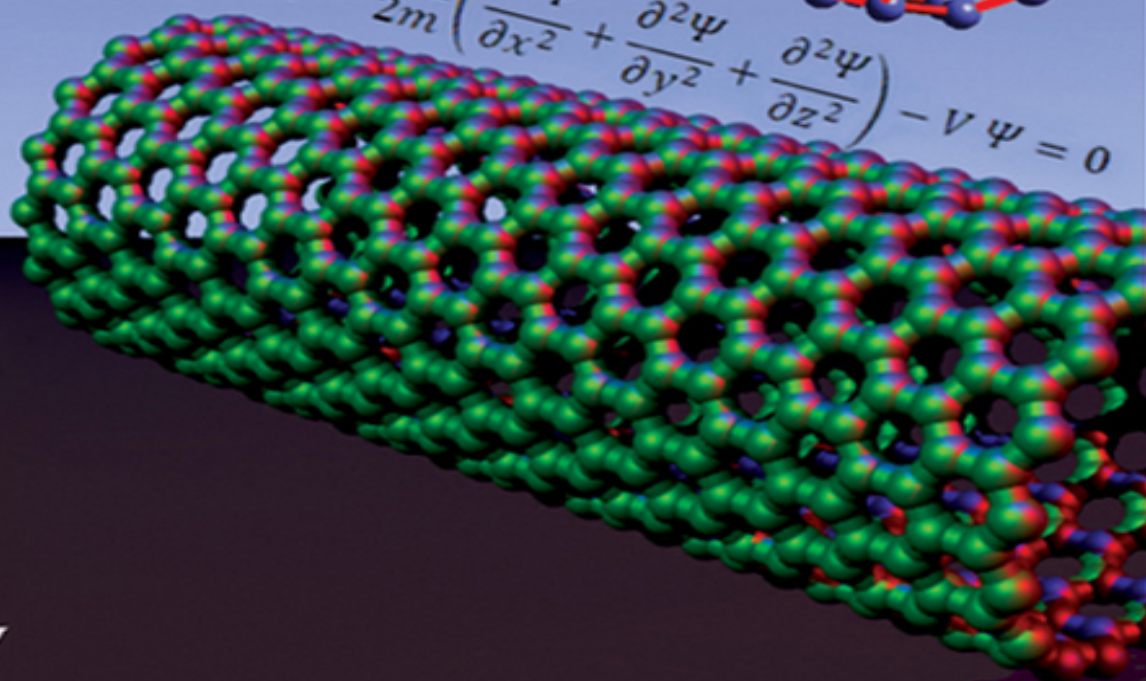
# Quantum Physics for Scientists and Technologists

Fundamental Principles and Applications for  
Biologists, Chemists, Computer Scientists,  
and Nanotechnologists

*Paul Sanghera*



$$i\hbar \frac{\partial \psi}{\partial t} + \frac{\hbar^2}{2m} \left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right) - V \psi = 0$$



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**Fundamental Principles and  
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and Nanotechnologists**

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*Former Research Scientist at CERN and Cornell*

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## ***About the Author***

Dr. Paul Sanghera, an educator, scientist, technologist, and an entrepreneur, has a diverse background in major fields on which nanoscience and nanotechnology is based including physics, chemistry, biology, computer science, and math. He holds a Ph.D. in Physics from Carleton University, Canada; a Master degree in Computer Science from Cornell University, U.S.A; and a B.Sc. from India with triple major: physics, chemistry, and math. He has authored and co-authored more than 100 research papers on the subatomic particles of matter published in well-reputed European and American research journals. At the world class laboratories, such as CERN in Europe and Nuclear Lab at Cornell, he has participated in designing and conducting experiments to test the quantum theories and models of subatomic particles. His current research interests involve topics in biotechnology, biochemistry, and molecular biology. In computer science, Dr. Sanghera has contributed to building such world class technologies as Netscape Communicator and Novell's NDS. As an engineering manager, he has been at the ground floor of several startups. A former lecturer at San Jose State University, he has taught a wide spectrum of courses at institutions all across the globe including India, Canada, and the United States. Dr. Sanghera is the author of several best selling books in the fields of science, technology, and project management. He lives in Silicon Valley, California.

## ***About the Tech Editor***

Dr. John Serri has held a variety of positions from basic physics research to application software development. His broad industrial and academic experience enabled him to develop a rigorous yet practical perspective to physics. Serri received his BS degree in Math and Physics from the State University of New York (SUNY) at Albany and earned a Ph.D. in Physics from the Massachusetts Institute of Technology where he developed novel techniques for using lasers to probe the dynamics of intermolecular collisions. The techniques he developed have led to numerous applications in basic physics including laser cooling, which led one of his mentors, Dr. William Phillips, to the Nobel Prize in Physics in 1997. After leaving MIT, Dr. Serri joined the staff at Bell Laboratories, where he conducted basic research in surface physics and applied research related to the effects of nuclear weapons on telecommunication systems. Later he joined the staff of Loral Aerospace and was one of the designers of the Globalstar System. At Globalstar, he led the development of the systems to control and manage the Globalstar network. Serri currently serves on the adjunct faculty of the Mathematics and Computer Science Department at California State University East Bay and is Vice President of Strategic Initiatives at Manhattan Software Inc., a major provider of Advanced Integrated enterprise software.

# Periodic Table of the Elements

Period	Group										Group								
	1											13	14	15	16	17	18		
	IA											IIIA	IVA	VA	VIA	VIIA	VIIIA		
	1A											3A	4A	5A	6A	7A	8A		
1	H 1.008																He 4.003		
2	Li 6.941	Be 9.012											B 10.81	C 12.01	N 14.01	O 16.00	F 19.00	Ne 20.18	
3	Na 22.99	Mg 24.31	Al 26.98	Si 28.09	P 30.97	S 32.07	Cl 35.45	Ar 39.95											
4	K 39.10	Ca 40.08	Sc 44.96	Ti 47.88	V 50.94	Cr 52.00	Mn 54.94	Fe 55.85	Co 58.47	Ni 58.69	Cu 63.55	Zn 65.39	Ga 69.72	Ge 72.59	As 74.92	Se 78.96	Br 79.90	Kr 83.80	
5	Rb 85.47	Sr 87.62	Y 88.91	Zr 91.22	Nb 92.91	Mo 95.94	(98)	Tc 101.1	Ru 102.9	Rh 106.4	Pd 107.9	Ag 112.4	Cd 114.8	In 118.7	Sn 121.8	Sb 127.6	Te 126.9	I 131.3	Xe
6	Cs 132.9	Ba 137.3	La <sup>o</sup> 138.9	Hf 178.5	Ta 180.9	W 183.9	Re 186.2	Os 190.2	Ir 190.2	Pt 195.1	Au 197.0	Hg 200.5	Tl 204.4	Pb 207.2	Bi 209.0	Po (210)	At (210)	Rn (222)	
7	Fr (223)	Ra (226)	Ac (227)	Rf (257)	Db (260)	Sg (263)	Bh (262)	Hs (265)	Mt (266)	— ( )	— ( )	— ( )	114 ( )	116 ( )	118 ( )				

Lanthanide Series	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (147)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinide Series	90 Th 232.0	91 Pa (231)	92 U (238)	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

# ***Fundamental Physical Constants<sup>a</sup>***

<b>Quantity</b>	<b>Symbol</b>	<b>Value(s)</b>
Atomic mass unit or Dalton	amu, u, Da	$1.660538782 \times 10^{-27}$ kg $931.494028 \times 10^6$ eV/c <sup>2</sup>
Avogadro number	$L$ , $N_A$	$6.02214179 \times 10^{23}$ mol <sup>-1</sup>
Boltzmann constant	$k$	$1.3806504 \times 10^{-23}$ J K <sup>-1</sup>
Elementary charge	$e$	$1.602176487 \times 10^{-19}$ C
Gravitational constant	$G$	$6.67428 \times 10^{-11}$ m <sup>3</sup> kg <sup>-1</sup> s <sup>-2</sup>
Mass of electron	$m_e$	$9.10938215 \times 10^{-31}$ kg $8.18710438 \times 10^{-14}$ J/c <sup>2</sup> $0.510998910$ MeV/c <sup>2</sup> $5.4857990943 \times 10^{-4}$ u
Mass of proton	$m_p$	$1.672621637 \times 10^{-27}$ kg $1.503277359 \times 10^{-10}$ J/c <sup>2</sup> $938.272013$ MeV $1.00727646677$ u
Molar gas constant	$R$	$8.314472$ J K <sup>-1</sup> mol <sup>-1</sup> $0.08205746$ L atm K <sup>-1</sup> mol <sup>-1</sup> K for kelvin
Permeability of vacuum Magnetic constant	$\mu_0$	$4\pi \times 10^{-7}$ N A <sup>-2</sup> N for newton and A for ampere.
Permittivity of vacuum Electric constant	$\epsilon_0$	$8.854187817 \times 10^{-12}$ F m <sup>-1</sup>
Planck constant	$h$	$6.62606896 \times 10^{-34}$ J s $4.13566733 \times 10^{-15}$ eV s $6.62606896 \times 10^{-27}$ erg s
Speed of light in vacuum	$c$	$2.99792458 \times 10^8$ m/s
Stefan-Boltzmann constant	$\sigma$	$5.670400 \times 10^{-8}$ W m <sup>-2</sup> K <sup>-4</sup> W for watt

[a](#) Courtesy of the National Institute of Standards and Constants (NIST).

# ***Important Combinations of Physical Constants***

<b>Quantity</b>	<b>Symbol</b>	<b>Value(s)</b>
Bohr magneton	$\mu_B = \frac{e\hbar}{2m_e}$	$927.400915 \times 10^{-26} \text{ J T}^{-1}$
Bohr radius	$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2}$	$0.52917720859 \times 10^{-10} \text{ m}$
Compton wavelength	$\lambda_c = \frac{h}{m_e c}$	$2.4263102175 \times 10^{-12} \text{ m}$
Molar gas constant	$R = N_A k$	$8.314472 \text{ J K}^{-1} \text{ mol}^{-1}$ $0.08205746 \text{ L atm K}^{-1} \text{ mol}^{-1}$
Rydberg constant	$\mathcal{R}_\infty = \frac{me^4}{4\pi c \hbar^3 (4\pi\epsilon_0)^2}$	$1.0973731568527 \times 10^{-7} \text{ m}^{-1}$
Speed of light	$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$	$2.99792458 \times 10^8 \text{ m/s}$
—	$\frac{1}{4\pi\epsilon_0}$	$8.98755 \times 10^9 \text{ m F}^{-1}$ F for farad, a unit of capacitance
—	$\hbar = \frac{h}{2\pi}$	$1.054571628 \times 10^{-34} \text{ J s}$ $6.58211899 \times 10^{-16} \text{ eV s}$
—	$hc$	$1.9864 \times 10^{-25} \text{ J m}$ $1239.8 \text{ eV nm}$
—	$hc$	$3.1615 \times 10^{-26} \text{ J m}$ $197.33 \text{ eV nm}$

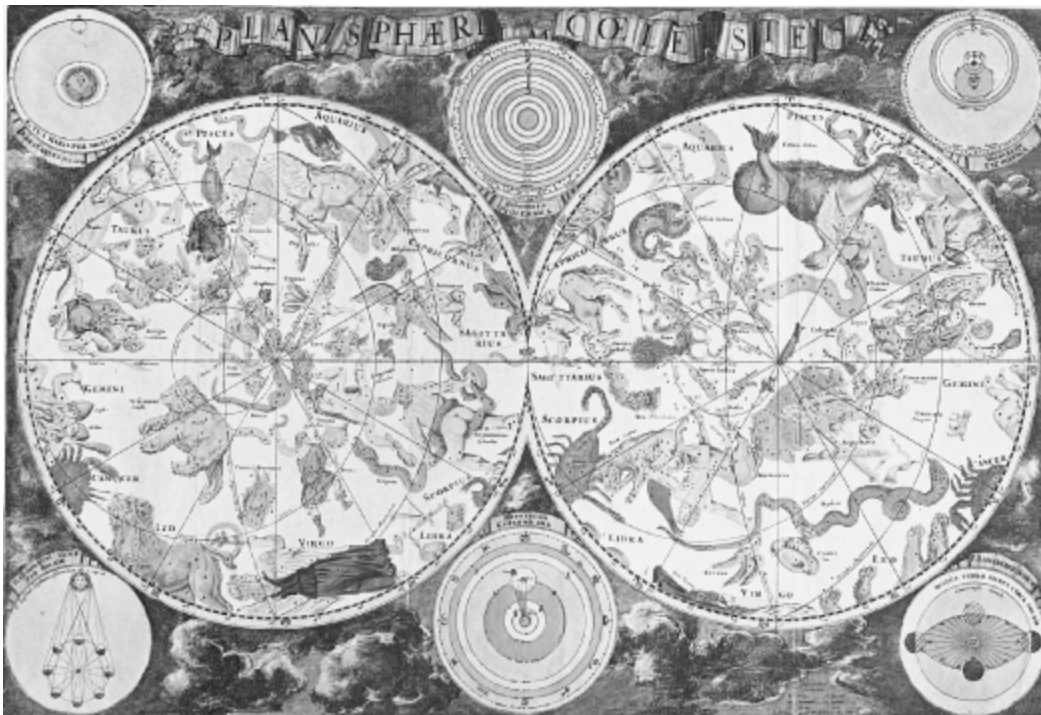
# *Preface*

## **Science, Technology, and Quantum Physics: Mind the Gap**

Quantum physics thus reveals a basic oneness of the universe.

*Erwin Schrodinger*

**Figure P.1** Celestial map from the seventeenth century, by the Dutch cartographer Frederik de Wit (1630–1698).



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## **P.6 In This Book**

### **P.7 Back to the Future**

To an artist, in Shakespeare's words, All the world's a stage. Taking this metaphor to another level, to a scientist, the whole universe is a colossal party with a cosmic dance on dance floors at all levels, ranging from an expanding universe with swirling galaxies, to planets revolving around their suns, to organisms of all shapes and sizes dancing through their life cycles, to molecules in action inside living and nonliving systems, to atoms making and breaking bonds to make molecules and crystals, to electrons dancing around the nucleus of atoms, and so on. The universe and everything in it, living and nonliving, originally started (and still starts) at the microscopic level, a level too small for human senses to resolve. In this book, we focus on the concept of micro in contrast to that of macro; micro means anything small enough not to be seen by the naked eye, including the size scales of micrometers, nanometers, and smaller items. Because the universe and everything in it is comprised of microentities, to fully understand the macro we need to understand the micro.

Humans, the macrobeings, have evolved to a relatively advanced level. For better or for worse we are late comers to this party of life on Earth. On the scale of a 12-h clock, if the party started at the hour zero (i.e., midnight) with the solidification of the earth's crust, and if it is noon now, we have just arrived at 11:59:59. However, now that we have arrived, we are the most curious and ambitious creatures at the party. We want to know everything about everyone and everything in the party: Who (or what) are you? What are you made of? How did you get here? Where are you from, no I mean where are you originally from? Where are you headed, that is, what is your future?

All the answers accumulated from our age old queries have uncovered the three most important higher-level

secrets of nature, important and general enough that they should become part of the thinking of scientists and students of all sciences.

## **P.1 THREE SECRETS OF NATURE**

At first glance, the diversity around us is obvious and ubiquitous. However, during the entire history of the development of science, the history of discoveries and inventions, nature has taught us a very powerful lesson over and over again: Look for the underlying unity behind apparent diversity of things and phenomena, and therefore behind the laws governing those things and phenomena. In my opinion, the three most salient of all the secrets of nature that science has discovered so far are the following:

*There Is an Underlying Unity Behind Apparent Diversity.*

This concept is a key point to understanding not only the things and phenomena around us, but also their diversity. For example, all life is made up of the same basic building block of life: the cell. Most great discoveries and breakthroughs in the history of science have revealed this secret over and over again: unity behind diversity.

*All Macroscopic Things Are Composed of Smaller Building Blocks.* This truth exists at various levels. For example, all materials around us are made up of molecules or crystals, all molecules and crystals are made of atoms, which in turn are made of subatomic particles (proton, neutron, and electron), protons and neutrons are made of quarks, and so on. This is also true about living organisms. For example, we are made of organs, organs are made of tissues, tissues are made of cells, cells are made of and run by the molecules of life and atoms or ions, and the molecules of life are made of atoms, and so on. This structural hierarchy is also apparent in our own inventions, for example, there are rooms contained in

buildings, the buildings are contained in neighborhoods, and the neighborhoods make up a City, and so on.

*Nature Does Its Most Important and Fundamental Work on a Smaller Scale.* This statement means that if you really want to understand a macroscopic structure, you will need to understand its smaller building blocks. The bottom line is we cannot have the macroworld without the existence of a microworld

The underlying unity behind diversity has been the key to major breakthroughs in the sciences. The history of physics can be told in terms of discovering the unification of multiple forces. For example, the terrestrial force that keeps us bound to the Earth and the celestial force that keeps the planets bound to the Sun are the same force: gravity. This realization helped Newton formulate the law of universal gravitation that applies to earth-bound problems, as well as explains the empirical laws of planetary motion discovered by Kepler. Unifying theories of electric and magnetic forces into a single theory of a force, called the electromagnetic (EM) force, was another great feat in physics, and the classical theory of EM is based on this unification. We now know from physics that our universe is shaped and governed by four fundamental forces: gravitational, EM, weak nuclear, and strong nuclear forces. For many, this may be unity enough, but the attempts to discover further unification continued, and there is great scientific evidence that even these four forces are different low-energy manifestations of a single force that was in action at the very beginning of the creation of the universe.

This history of unification of forces is intertwined with the history of discovering and understanding the smaller and smaller building blocks of matter. For example, physicists (and chemists) discovered that all materials around us are made of smaller components called molecules; the molecules are made of even smaller components called

atoms; and atoms in turn are made of yet smaller constituents called neutrons, protons, and electrons. Physicists have probed neutrons and protons, and have discovered that they are made of even smaller and more fundamental particles called quarks. Therefore, the path of development that physics, and as a result other disciplines of science, have taken is the path from the macro (large) to the micro (small). As mentioned earlier, the reason for this is that we, the humans, are macrobeings and we started observing things with the most primitive tools, our five senses (e.g., our eyes), which were the only tools easily available to us. These tools are limited to the macroworld. However, to our advantage, we humans had a capability that other organisms did not have, and that is, to develop tools and techniques: say technology. The gradual development of technology, and hence better tools (e.g., microscopes), enabled us to continue our journey of understanding and exploration from the macroworld of planets and visible objects around us to the microworld of molecules, atoms, and subatomic particles. In fact, by extending this idea we find there is a feedback loop between technology and basic fundamental science. As science evolves, new technologies emerge and in turn these new technologies allow for the creation of better and more powerful scientific tools. These tools in turn allow for new observations that lead to an even better understanding of the microscopic world, and so the cycle goes. For example, the colossal colliders at the particle physics lab at CERN (near Geneva, Switzerland) would not be possible without the capability of tracking particles to the precision of micrometers and microseconds provided by this technology, which itself is based on physics.

Combining the three secrets of nature, the truths of unification and the unity behind diversity are essential to our journey from the macro to the micro. This relationship

among these three secrets of nature is the reason it has taken us this long to find them: the whole history of the development of science on this planet.

Rather ironically, when we had less information and knowledge than we have today, it appeared as if one person could know everything, and there was only one discipline called *natural philosophy*, the study of nature and the physical universe. Today's physics is actually the modern version of *natural philosophy*.

## **P.2 FROM NATURAL PHILOSOPHY TO PHYSICS**

In olden times, natural philosophy referred to the study of nature and the physical universe. It served as a precursor to developing fields of natural sciences led by physics. Rest aside physics, modern notions of *science* and *scientists* date only to the nineteenth century. Before then, the word "science" simply meant knowledge and the title *scientist* did not exist. For centuries, scientists were called natural philosophers, and these practitioners often pursued a wide variety of interests. A remnant of that heritage is a doctorate in physics, or other sciences, which is still called a Ph.D., and is an abbreviation for doctor of philosophy. The title of Isaac Newton's scientific treatise published in 1687, commonly known as the Principia, is called *The Mathematical Principles of Natural Philosophy*. So, it is not a coincidence that long-established Chairs of Natural Philosophy at older universities are currently occupied largely by physics professors. The connection between physics and other disciplines of science can also be understood from the fact that all other fields of science are historically developed from natural philosophy or its descendants. During the fourteenth and fifteenth centuries,

the term *natural philosophy* was referred to what is now called physical science. By the mid-nineteenth century, with the increase of information and knowledge, it became increasingly clear that it was not generally practical for scientists to contribute to numerous areas. Thus specialization occurred and now there were physicists, chemists, biologists, geologists, and so on.

## **P.3 PHYSICS THE MOST FUNDAMENTAL SCIENCE**

Being the most fundamental of all the sciences, physics has profoundly affected all science fields. Given its fundamental nature, students in many fields are required to take some physics courses in order to understand the fundamental principles underlying many phenomena across many science disciplines. In this sense, physics is intimately related to other sciences, and also to applied fields, such as engineering, medicine, and now nanotechnology. This is because principles discovered in physics apply to all natural sciences. For example, the principle of conservation of energy is common to all physical and chemical systems.

Chemistry is the scientific study of matter and materials and the changes that they undergo; matter is anything that exists, has mass, and occupies space; whereas a material is any kind of matter that can be used for something, such as glass. Starting with the macroworld as physics did, early chemistry largely dealt with substances, such as extracting metals from their ores, making pigments for cosmetics and painting, and fermenting beer and wine. Chemistry is the science that not only is most affected by physics, but also overlaps or collaborates with physics in many areas of study, such as atoms, molecules, and collections of atoms and molecules. A great example of the interaction between

physics and chemistry is the quantum mechanical explanation of the relationships among chemical elements and the rules of their interaction (reactions) with one another captured in the periodic table.

Biology is the scientific study of life; that is, the study of living things and the phenomena related to them. Like physics and chemistry, biology also began its journey in the macroworld: finding and studying things that you can see with your naked eye, doing the counting, classifying them, and so on. By now, however, biology has progressed into the microworld in different disciplines, such as microbiology, biochemistry, and molecular biology. There are an enormous number of physical phenomena involved in developing a single cell into an organism and then maintaining the organism. In order to fully understand life, all these phenomena will be understood in terms of the principles of physics. Many key advances in the biological sciences already have been made possible by physics-based techniques. Some examples being used to study the molecules of life are the optical microscope to study cells, X-ray diffraction used to discover the structure of the deoxyribonucleic acid (DNA) molecule, and the electron microscope. Nuclear magnetic resonance (NMR), a quantum mechanical phenomenon, is revolutionizing the field of medicine in the form of magnetic resonance imaging (MRI). With developments in genetics and molecular biology, an overwhelming amount of data is being generated in biology. The only way biologists will be able to fully make sense of these data is by developing a theoretical framework based on physics principles. Quite possibly in this process, we will discover new physics laws, partly because biological systems are generally different in some important ways from the physical systems that led to the current physics laws. After all, during its early days, biology helped physics in the discovery of the principle of conservation of energy.