SANJAY JAIN & VIVEK NANOTI

Science and Engineering —A Seamless Merger?

Scientific research is playing an increasingly important role in the field of engineering. It can be aptly said that today's research in science becomes the engineering of tomorrow.

SCIENCE and engineering are inseparable. Science discovered how birds fly and engineering used this knowledge to build airplanes. Science explained how lightning occurs and engineering used this understanding to build electrostatic devices. Science explored how organisms behave in groups and engineering used these insights to develop computer algorithms. These are just a few of the myriad examples of how science and engineering are seamlessly merged in the story of human development.

The word science originates from the Latin word scientia that means 'to know'. Technology deals with application of scientific knowledge and engineering relates to practical use of appropriate technologies to create desired structures and designs. *Encyclopaedia Britannica* (macropaedia, Vol. 18) defines engineering as the professional art of applying science to the optimum conversion of the resources of nature for the use of mankind. As engineers use scientific principles to develop economical solutions to technical problems, science becomes an intrinsic and inseparable part of the entire engineering process.

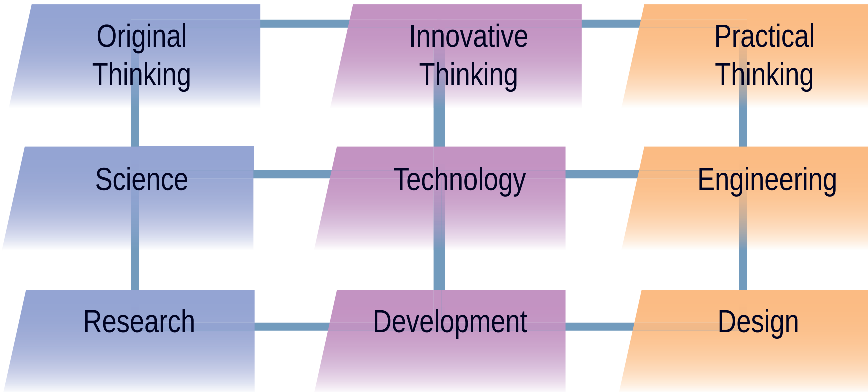


Fig 1. Interdependence of science, technology and engineering

Let us put it this way: the function of the scientist is to know, while that of the engineer is to do. Scientists accumulate verified, systematized knowledge of the natural world and engineers bring this knowledge to bear on practical problems. Engineers convert thoughts into actions, ideas into reality and theories into practice. The professional maturity of an engineer thus demands a sound base of science. The close interdependence of science, technology and engineering can be expressed as shown in the Figure 1.

While it is difficult to grow crystals in a laboratory (left), crystals as big as 10 m have been found in the Pulpí geode in Almería

Seamlessness in Nature

In nature's unendingly open and vast laboratory there are myriad examples of science merging seamlessly with engineering. For example, crystals, which can be understood as orderly arranged atoms (crystal physics) and can be grown in laboratory (crystal growth technology), are available in nature in an awesome variety of sizes and shapes. More than 90% of the naturally occurring solids are crystalline that include minerals, rocks, sand, snowflakes, ice, clay, gems, jewels, metals and several crystals produced by living organisms. While it is difficult to grow single crystals of even a small dimension in a laboratory, single crystals in excess of 10 m have been found in the Pulpí geode in Almería in southern Spain and crystal caves in Naica (Mexico).

Let us look at another example. While nuclear engineers have been struggling to produce energy by nuclear fusion on earth, there are many stars in nature that produce a lot of energy by this process.

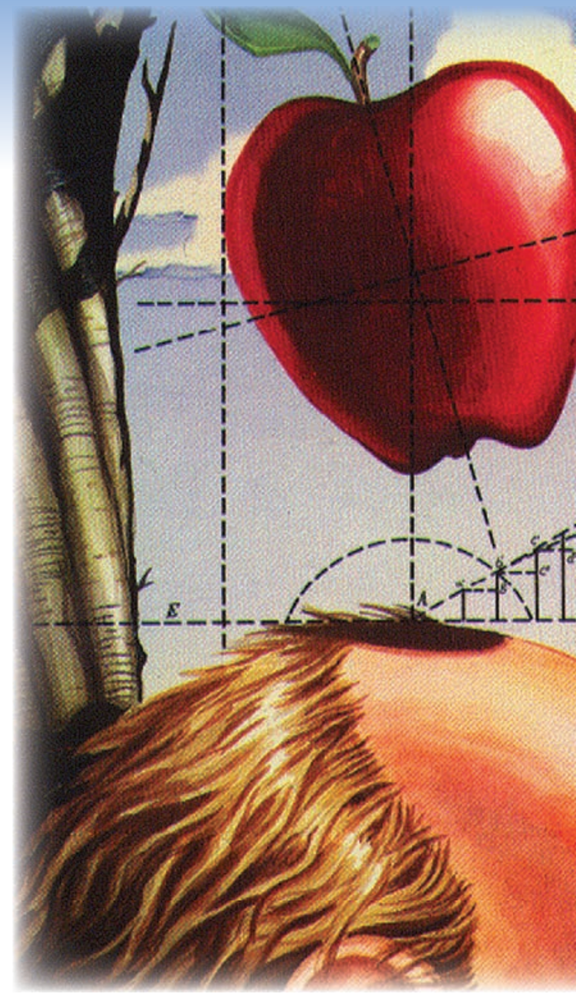
The human urge to understand nature is as old as humanity and for this reason science was formerly known as natural philosophy. However, in the modern sense of the term science came to be understood as the pursuit of knowing nature by seeking agreement between theory and experiment, a method known as scientific method. The period from the 15th to 17th centuries witnessed a revolution in scientific thinking and science emerged as an autonomous discipline, distinct from both technology and philosophy.

In the last three centuries use of scientific method brought to fore a vast treasure of knowledge of the natural world. As this knowledge deepened, its application widened ever improving the scope of technological sophistication. However, the unending treasure of nature's knowledge has always kept the scope of sophistication alive. Marvels of nature's engineering inspire emulations of nature in a more and more creative way. Table 1 shows a few examples of how nature provides inspiration to scientists and engineers in several ways.

Table 1. Examples of science and engineering inspired by nature

	The Wright brothers, who succeeded in flying the first aircraft in 1903, derived inspiration from observations of pigeons in flight.	
	Emission of light by firefly (bioluminescence) inspired new innovations in lighting technology. Electroluminescent LEDs are examples of this innovation.	
	Bats see by "ultrasonic eyes". They emit ultrasonic waves and on the basis of the echoes received from a particular object they decipher the information about the motion and location of that object using the phenomenon of Doppler shift. Techniques such as ultrasonography and echocardiography have been developed on similar lines that enable imaging and knowing details of the internal organs of human body. Radar uses radio waves to determine the range, altitude, direction, or speed of objects in a similar way.	
	By studying the shape of the Kingfisher's beak – a bird that excels at diving – researchers were able to improve the aerodynamics of high-speed trains in Japan when they enter tunnels.	
	The boxfish was used as inspiration for Mercedes-Benz's bionic car concept because of its aerodynamically efficient shape.	
	The invention of Velcro in 1948 by George Mestral was inspired by the burrs of burdock that stuck to his clothes. Upon examination under a microscope, he noted their hundreds of hooks with a loop that caught on clothing, animal fur or hair.	

Left: Ant behavior: inspiration for computer engineers
Above: Marco Dorigo



Apart from these individual examples, nature also offers several inspirations based on the way in which organisms behave in groups. For example, computer scientists and engineers have developed computational approaches and algorithms based on what is called swarm intelligence. According to it, the swarms of the organisms like ant colonies, bird flocking and bacterial growth seem to be more intelligent than any of the individuals within it.

Consequently, Ant Colony Optimization was proposed by Marco Dorigo in 1992 via an algorithm called `Ant System'. The principles of swarm intelligence have also been applied to study the collective behavior of large number of small and simple robots leading to an area of research called swarm robotics.

Developments in nanotechnology have also been guided by several motivations from nature. For example, living cells and viral capsids, like nature's nanomachines, provide clues for construction of nanodevices. The observation of designs and patterns in nature and their imitation to build engineering applications in a sustainable way has led to the evolution of a relatively new science called biomimetics or biomimicry.

The journey of the developments in science and engineering is thus a story of their working hand in hand – complimentary rather than contradictory, collaborative rather than competitive. Discoveries in science are outputs of a researcher's enquiries into nature's secrets and serve as inputs for the world of engineering and technology. Table 2 lists a few examples of this type.

Seamlessness among Professionals

As science enjoys an appreciable overlap with engineering and technology there have been happy interflows of knowledge between scientists, technologists and engineers leading to their mutual development. The advancement of technology also aided the growth of science just as science aided the growth of technology. The close links between science and engineering can be best appreciated by examples of several engineers who contributed to science and several scientists who contributed to engineering during the practice of their profession.

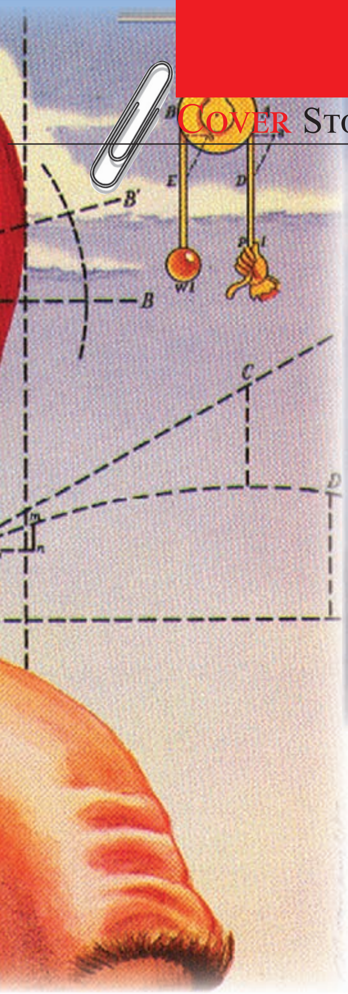
Table 3 enlists a few of the many such examples found in history.

Seamlessness in the World of Work

Knowledge of scientific processes is seamlessly subsumed in the engineering world of work, i.e., in the design of products and execution of projects. For

TABLE 2. CURIOUS ENQUIRY, RESEARCH OUTPUT AND APPLICATION

Curious enquiry into nature's secret	Research output	Fields of application
Why objects thrown up come down?	Newton's theory of gravitation	Rocketry, Space Technology
How charges attract and repel each other? Why a magnetic needle kept near a current-carrying wire deflects?	Coulomb's law of electrostatics, Oersted's theory of electromagnetism, Maxwell's theory of electromagnetic waves	Electrical engineering, Telecommunication engineering
Why electrons come out when light falls on certain metals and how coherent light can be produced?	Einstein's theories of quantum nature and stimulated emission of light	Optoelectronics, Photonics, Quantum engineering, Laser technology
How plants inherit patterns of traits?	Laws of Mendelian inheritance	Genetic engineering
If radiation can show particle property, why matter can't show wave property?	de Broglie's theory of matter waves	Electron microscopy
Why different solids have different electrical properties?	Band theory of solids	Semiconductor technology, Electronics engineering



Newton's apple to rocket science

Let us put it this way: the function of the scientist is to know, while that of the engineer is to do.

example, if certain manufacturing parts need to be thoroughly cleaned and the conventional techniques do not suffice, science of ultrasonic cleaning process can be exploited by an engineer who can design an ultrasonic generator and the parts to be cleaned can be carried by a conveyer through a bath tank in which ultrasonic energy could clean them.

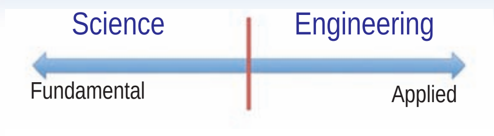
Another example is the wide application of the principle of resonance. Resonance is a phenomenon in which any given system, driven by another vibrating system, oscillates with maximum amplitude when the frequency of the driving system matches the natural frequency of the driven system. Organ pipes, vibrating strings, microwave cavities and laser cavities are a few examples of resonating systems. In the design of products, engineers have to ensure that the resonant frequencies of the component parts do not match driving frequencies of motors or other oscillating parts.

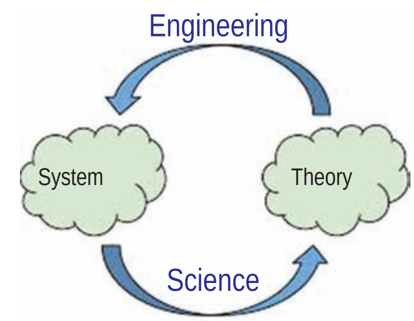
The principle of anti-resonance is used in saving structures from damage or failure by devices called tuned mass dampers. They reduce the amplitude of mechanical vibrations by moving back and forth with a phase that tends to damp the movement of the structure. These devices are used widely in structures ranging from civil structures like bridges and buildings to that in power transmission and automobiles. The first such damper in the United States was placed within the 250 m tall Citicorp building in New York.

TABLE 3. EXAMPLES OF SEAMLESSNESS AMONG PROFESSIONALS

	Augustin Fresnel, the French military engineer, was curious about various effects light exhibits and made pioneering contribution to the science of interference and diffraction of light.	
	Wallace Sabine was an American physicist who founded the field of architectural acoustics. He pioneered this field while handling the assignment of improving the acoustics of the Fogg Lecture Hall at the Harvard University.	
	Jack Kilby, an engineer at Texas instruments, proposed a revolutionary concept of creating all components of an electronic circuit in a single semiconductor chip, called an integrated circuit (IC) in 1958 for which he received the Nobel Prize in physics in 2000.	
	Stephan Wolfram, a particle physicist, developed an advanced computer software called Mathematica.	
	Physicists Allan Cormack and Peter Mansfield were awarded Nobel prizes in medicine in the years 1979 and 2003, respectively, for pioneering the development of techniques of x-ray computer tomography and magnetic resonance imaging. *Allan Cormack* *Peter Mansfield*	
	Dirac, a student of electrical engineering, switched on to science to know more about the relativistic quantum theory and went on to speculate the existence of positron as an antiparticle of electron.	
	Bardeen, who studied electrical engineering at University of Wisconsin and solid state science at Princeton University, was the first person to receive Nobel Prize twice in science for his role in the discovery of transistor (1948) and development of the theory of superconductivity (1957).	

Tuned mass damper in Taipei 101 building





Today many buildings use damping of this type. A thorough scientific analysis of resonance is of immense help to engineers in ensuring the safety of various structures and products.

We can understand the seamlessness of science and engineering using the analogy of a tree. The roots of the tree signify various fields of basic scientific research. Areas having more unsolved challenges form the fertile areas of research meaning deeper roots. Results of investigation that pass the test of time take the form of established knowledge that can be compared with the stem of a tree. Utilitarian value of knowledge results in development of branches that signify the world of engineering and technology. New discoveries in science leading to new applications can be compared with new roots of a tree leading to new branches.

Thus, the 'branches of engineering' can be traced to 'roots of science'. For example, branches of electrical and electronics engineering emerged from the roots of physics: the first courses in electrical engineering were introduced in the physics department of the MIT in 1882 and were followed shortly by similar courses at Cornell University. By 1890 there were 10 such courses in the physics departments of major US universities. In the UK, formal electrical engineering education usually began within the discipline of physics.

Here are some more examples of branches of engineering traced to their roots in science:

• Electrical engineering has roots in the pioneering scientific research of James Maxwell who summarized the basic laws of electromagnetism (Maxwell's equation;

TABLE 4. EXAMPLES OF SCIENTIFIC PRINCIPLES USED IN THE ENGINEERING WORLD

Scientific principle	Use in the engineering world
Vibration and propagation of noise control sound waves, echo and reverberation	Engineers use these principles in the technologies of recording and reproduction of sound waves, (architectural acoustics and engineering acoustics), production and transmission of speech (communication acoustics) and in the work related to acoustics of living systems (physiological acoustics, animal acoustics, medical acoustics and biomedical engineering). These principles are also used in aerospace engineering (sonic boom, supersonic aircraft, wind tunnel etc.); space technology (rocket combustion, oscillations etc.); nuclear engineering (nuclear bomb blasts, controlled fusion in plasma, etc.) and earthquake technology (seismic waves).
Interference of light waves	Interferometric techniques are used in engineering works such as testing of flatness of optical surfaces, testing of prisms and lenses for chromatic aberrations, measurement of thickness of thin films, collimation testing and measurement of wedge angles.
Total internal reflection of light	This phenomenon is used in fiber optic technology, fiber optic endoscopy and fiber optic sensor technology.
Photoelasticity (stress-induced birefringence)	Civil and mechanical engineers use this principle to simulate the stress distribution by application of load to transparent plastic models of structures to check and optimize their design. It is commonly used for engineering components such as gears, turbine blades, beams and windshields.
Desalination of water	Chemical engineers use this phenomenon to design and build large-scale processing plants for producing purified water. Today, millions of gallons of water are being desalinated by flash evaporation, which uses evaporation and condensation phenomena, and by reverse osmosis, which uses molecular membrane technology based on membrane diffusion principles.

1864) and predicted the existence of radio waves, which were experimentally demonstrated by Heinrich Hertz in 1887. Early roots can also be traced to the works of Andre Ampere, George Ohm (early investigators of electricity), Charles Coulomb (Coulomb's law of electrostatics, 1785), Alessandro Volta (electric cell, 1800), Hans Oersted (electromagnetism, 1820), Michel Faraday and Heinrich Lenz (electromagnetic induction, 1840s).

• Electronics engineering emerged from the roots of the contributions from Edison (incandescent lamp, 1878), Hendrick Lorentz (electron theory of electric charge, 1895), Sir J.J. Thomson (e/m for electron, 1897), Lee De Forest (triode, 1907), V.K. Zworykin (demonstration of CRO, 1920) and John Bardeen, William Brattain, and William Shockley (transistor, 1948). The word 'electronics' has been coined as a contraction of 'electron mechanics'.

• The roots of mechanical engineering can be traced to the scientific works of several scientists that include Robert Boyle (Boyle's law, 1662), Robert Sterling (second law of thermodynamics, 1816), N.L. Sadi Carnot (engine's concept, 1824), Julius Mayer (equivalence of heat and work, 1842), James Joule (relation between heat and work, 1850), Rudolf Clausius (kinetic theory, 1854; entropy, 1865), and Joseph Stephan (heat transfer mechanisms, 1879).

• Civil engineering (the term used by John Smeaton in 1782 to differentiate his non-military engineering work from that of the military engineers) has its roots in the scientific contributions of Robert Hooke (Hooke's law, 1679), Isaac Newton (Principia, 1687), Amontons (laws of friction, 1699), John Bernoulli (principle of virtual work, 1717), Coulomb (laws of friction, 1779), Lagrange (principle of virtual work, 1788) and David Brewster (photoelasticity, 1816).

• Nuclear engineering has its roots in the pioneering works of scientists Henry Becquerel (radioactivity 1896), Marie and Pierre Curie (radium and polonium, 1898) Ernest Rutherford (alpha particle scattering, 1911; proton, 1914; splitting of atom, 1919), James Chadwick (neutron, 1932), Otto Hahn (fission, 1938), Enrico Fermi (first fission reaction, 1934; first nuclear reactor, 1942) and C.L. Cowan and F. Reines (detection of neutrino, 1953).

Many disciplines that originated as research areas in science later grew into autonomous fields and got separated from science. Emergence of new fields of knowledge and application, based on the discoveries in science, can be likened to seeds of ripened fruits of a tree growing into new trees. The close connection between basic research in science and its applications to technology is obscured sometimes just as taller branches of a tree seem to be unrelated to its deeper roots. However, the oneness of a tree exudes the unification that nature manifests – application of knowledge cannot be de-linked from acquiring knowledge through basic research.

Today's Science Research is Tomorrow's Engineering

Today science and technology are evolving at a rate faster than ever before and the time lag between research breakthroughs in science and their applications to engineering has been shrinking rapidly. For example, it took very little time for the discovery of laser to move from the physics research laboratory into the applications in CD player and barcode scanner. Similarly, the knowledge of nuclei in magnetic fields (nuclear magnetic resonance) found quick application in medical diagnostics (magnetic resonance imaging).

Scientific research is thus playing an increasingly important role in the field of engineering. In fact, basic research at the forefront of physics and other sciences is included as one of the functions of electrical and electronics engineers [*Encyclopaedia Britannica* (macropaedia, Vol. 18)]. It can be aptly said that today's research in science becomes the engineering of tomorrow!

> Today's research in science becomes the engineering of tomorrow

The area in which the distinction between science and engineering seems to have almost disappeared today is that of the materials. Up to the 19th century application of materials in technology was limited by the knowledge of materials to a macrostructural level. However, advances in material characterization techniques brought forth knowledge at much deeper levels and the goals and efforts of materials scientists and materials engineers started overlapping more and more. Scientists, like artisans at the atomic level, enjoy researching into making materials behave in desired ways; they know the art of engineering the atoms.

These pursuits led to the discovery and development of several materials like semiconductors, superconductors, ferrites, composites, liquid crystals, metallic glasses, ceramics, alloys (solid solutions) and synthetic polymers which quickly moved into the category of engineering materials. New materials brought forth many new and novel applications.

A few examples are strong but lightweight alloys for aircrafts, fuels used in power plants, biomaterials used in heart valves and artificial kidneys, shatterproof car windshields, integrated circuits, steel-reinforced concrete, displays used in panel meters and ceramic tiles used in space shuttle.

New materials are bringing new surprises everyday and are changing our world in an unimaginable way. These dramatic advances remind us of the words of Goddard, "It's difficult to say what's impossible, for the dream of yesterday is the hope of today and the reality of tomorrow."

Dr. Sanjay Jain is Head, Knowledge Center, Priyadarshini Institute of Engineering and Technology, Nagpur. Address: Flat J-6, Janjeera Apartments, Plot No. 109, Laxminagar, Nagpur-440022. Email: sanjaylambade@rediffmail.com

Mr Vivek Nanoti is Principal, Priyadarshini Institute of Engineering and Technology, Hingna Road, Nagpur-440019; Email: viveknanoti@gmail.com