Convergence of Technologies—Nature's Benchmarks

By

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Engineers create things. They conceptualize, design, manufacture, install, use (for and by the world at large), maintain and dispose thousands or even millions of products every day. From a simple toy to a space shuttle, from a bicycle to a Boeing-777, from a simple calculator to a supercomputer, from an archaic soda-filling machine to a massive petro-chemical complex, from an ordinary hammer to a gigantic oil-rig, from a child's binoculars to the Hubble telescope, from a primitive hamlet of thatched-roof huts to sprawling cities, from a fire-cracker to a giant-rocket that can propel a probe towards the planet Mars, from a programmable loom to the Internet which has become the nervous system of the Earth, … and the list can go on.

We all know how engineers conceive, design, manufacture, install, use, maintain and dispose off consumer products, structures such as buildings and bridges, computers, communication gear, transportation devices, and machinery. If you take an unfussy electric bulb, it is manufactured from tungsten, glass and aluminum. When Thomas Alva Edison invented it in 1879, it had an efficiency of 1%. Today's LED lamps have 65% efficiency. Not only the conversion efficiency (electricity to light), but also, the design tools (to create new bulb designs), manufacturing methods (productivity), reliability, and disposal methods have tremendously improved. The first mechanical computer "Difference Engine" of Charles Babbage built in 1822 did not far exceed the speed of a clever human calculator. The engineers at the University of Pennsylvania who built ENIAC, the first electronic computer in 1946, had to intervene frequently to repair, restore, and restart it. Today's computers can go on with zero down-time atleast a few years in a row at astounding computational speeds. The first electric motor could turn only a few revolutions before it stopped for repair and human intervention. Now, there are motors that can run non-stop for a decade or so. Sizing a cloth and stitching a shirt used to take 10 hours or more. Now it is done in less than 30 minutes. With the micro-electronics added to the IC engines, the compression ratio has been pushed from 5 to 7 to 12 to 22 (race-car), increasing its efficiency. Today's hybrid cars deliver double the mileage, with the help of electronics and improved chemical battery technologies. Fuel cells are on the way to increase these efficiencies further and offer pollution-free transportation. Constructing a 3-bedroom home used to take months and years. Now, it can be done in 2 hours 45 minutes (present world record).

Multi-location factories were managed as isolated systems. These days, ERP (Enterprise Resources Planning) systems connect them into a coherent whole. Great strides have been made on all fronts including design, analysis, construction, inspection, conversion, manufacturing, power generation, factory management, computers, software, logistics, storage and distribution. With their relentless pursuit for excellence, engineers have created and normalized innumerable technologies with increasing efficiencies. The recorded evidence of this—*from cave-men to Leonardo da Vinci to present times*—is available in the annals of history.

Though admirable for their achievements, even the world's best engineers do not come anywhere near Nature's ingenuity. Their engineering feats and triumphs are mere child's play before the super intelligent Mother Nature. Their creations pale before her engineering accomplishments. Let me illustrate.

Much before engineers started making things, NATURE has been creating things, in varieties and quantities unimaginable to the human mind. She creates energy (in the Sun by nuclear fission and fusion, for example); food (Photosynthesis); organs (eyes, sensors, brains, stomachs, skins, levers, kidneys, skeletons, muscles, hands, legs, wings, fins, tails); organisms (plants, trees, insects, fishes, birds, reptiles, animals); ecosystems (a Serengeti, an Okavango, an Amazon river-basin, a rain-forest, a prairie, a fresh-water lake, a coral-reef, a tidal-ocean); cycles (water, oxygen, nitrogen, carbon dioxide cycles) … and so on. Most of Her technologies are executed at ambient temperatures and pressures, without the use of harsh chemicals, and are efficient (require least energy), non-polluting and eco-friendly. Consider an example: Lens manufacturing. Engineers create them chiefly from glass (Silica) for use in eyewear, cameras, microscopes, telescopes, and such devices. Glass is melted in a furnace, purified, poured into molds, cooled, ground, polished, tested and dispatched for assembly. The quantity of lenses manufactured by humans may not exceed a few million per day. Nature also creates lenses, trillions of them every second. Consider these numbers: 15,000 children are born every day. They need 30,000 lenses (2 per head). Millions of creatures—butterflies to buffaloes, mice to elephants, dogs to deer, snails to snakes, spiders to eagles—are born every day. They all need lenses, 2 per head (spider needs 8). Perhaps, a million dragon flies are born during the season in a patch of forest land. Each dragon fly needs 64,000 lenses (32,000 per eye). A million flies would need 64 billion lenses. A mosquito or a fruit fly needs similar quantity of lenses for its vision, navigation and protection. How many anchovy, krill, fishes and crustaceans are born in one cubic kilometer of a sea? Trillions! They all need eyes (some 2 each, some 4 each, some 40 each). A crude estimate will lead us to a quantity of atleast a billion trillion (10^{18}) lenses per day. In the process of manufacturing these many lenses, Nature's choice materials, designs, manufacturing methods, technologies to achieve high reliability, maintainability, recyclability etc, far exceed the human imagination and intelligence. Even the best-in-the class designs that human engineers have created so far, are at best dim and dull before Nature's designs.

Nature's manufacturing intelligence is unequaled. Her choice of materials (organic lenses, organic light displays, organic motors, organic sensors, organic computers, organic food processing engines); her mechanisms (leaves, flowers, fruits, seeds, eyes, brains, ears, tongues, noses, teeth, bones, teeth, tusks, horns, muscles, skins, hearts, levers, stomachs, glands, lungs, proboscises, beaks, antennas, hands, legs, wings, fins, tails); her food production methods (harvesting the Sunlight by photosynthesis, a process that releases oxygen which enriches the atmosphere) etc, are all so advanced that even a hundred years from now, human engineers may not succeed in creating equivalent technologies. For instance, if we were to produce the oxygen with our current technology in the quantities that Nature produces, we would be polluting the Earth to death in a very short time, in a matter of days. A thrown plastic bag takes a thousand years to become part of Nature, which is simply insane. Nature gave us pure water (for example, rain water). But, we polluted it much (our factories, power-generation methods, automobiles are largely responsible) and idiotically we take pride in selling packaged drinking water, which is the biggest business scandal of the twentieth century. (What's next? Selling oxygen in canisters and inhalers mortgaging the future generations?!). On the other hand, there is not a single technology of Nature that has ruinous or dreadful by-products. Nature is the yardstick for perfection. The intention of this lecture is to show that wide 'gap' between human technology and Nature's equivalent technology and to share what's being done currently in the best labs of the world, and what must be done to close that 'gap', with a hope that all scientific efforts will ultimately benefit the humanity—an idea that is *arguable*.

To compare two similar technologies, we need some metrics. The metrics for assessing a technology are its usefulness, functionality, efficiency, longevity, manufacturability, assemblability, testability, identifiability (Uniqueness), uptime, safety, quality, reliability, maintainability, availability, change-over time, usability, adaptability, self-learning, self-defense, self-repair, self-healing, aesthetics, beauty, joy, portability, scalability, packability, transportability, remanufacturability, reusability, recyclability, growth, renewal (reproduction), disposability, etc. If you take a technology and a relevant metric or a set of metrics, then you can compare the human technology with Nature's technology. All most all the time, unfailingly and consistently, it turns out that Nature's is the best. For example, the efficiency of light production of a lowly firefly that we all see in sugarcane fields is 98% (versus 65% of Human's best). The human brain, which is Nature's creation, operates with 0% downtime over 70 years of life-span or even more. No computer that human engineers have created can come anywhere closer even on that one metric, let alone the additional set of metrics (efficiency, growth, scalability, self-learning, self-defense, self-repair, adaptability, networkability, recyclability) that we must consider when we evaluate a computer technology. A human heart runs 70 years or more without pausing for rest, while a tortoise' heart pumps even more, for about 400 years. Where are such motors in the realm of human technology? Nature crafted a human hand with 21 degrees of freedom, with millions of sensors on its skin that sense pressure, temperature and chemistry of substances it comes in contact with. An eyelid closes and opens to protect the eye atleast a billion times in a lifetime without ever making even a mild rasp or needing a repair. Each eye is equivalent to a 131 Mega pixel digital camera, and both eyes working in sync transmit about 400 billion bits of information per second to the brain. Brain analyzes it and makes decisions, about 20,000 per day for an average man. Brain is the most mysterious organic computer whose secrets (even a zillionth part) are not known yet. A boundless thing about the brain is, it doesn't need hardware upgrades even with exponential growth of knowledge around it. In other words, it never becomes obsolete, like our desktops and laptops (The pleasure of a new computer in our home or office, quickly transforms into the pain of replacement, in a matter of six-months—that is the status of our technology!). Scientists know that brain has not changed structurally atleast in the last 100,000 years. Similarly, each of the organs of the human body and of all creatures is extremely complex and work in varying degree of environments with amazing range of capabilities. The best robots of the world today—Honda's *Asimo*, Sony's *Qrio*, or Toyota's *Toybots,* each costing millions of dollars—look like hi-tech mannequins in terms of capabilities when evaluated against the natural body. Similar logic applies to almost all technologies that humans have created so far.

Take any technology. The gap between human technology and its equivalent in Nature, can be quite baffling even to the best brains of the world. During the seventies, when US Air Force Engineers benchmarked their radars vis-à-vis bats, they were dazed to discover that bats are a trillion times more efficient. Recently, some universities have initiated a systematic documentation of Nature's technologies so as to benchmark. These benchmarks can act as guide posts to develop advanced technologies. The goal of the best engineering labs and research institutions of the world such as MIT (Massachusetts Institute of Technology), CMU (Carnegie Mellon University), SRI (Stanford Research Institute), Rensselaer Polytechnic, CRN (Center for Responsible Nanotechnology) is to close this gap. Closing the gap would be possible only by the "*convergence*" of technologies. Again, 'convergence' is not a new thing. It has been there for many centuries. For example, when microprocessor was integrated with the conventional machines, CNC machines were born that revolutionized manufacturing. When quartz-movement replaced mechanical-movement in watches, it turned the watch industry upside down—Novice Japanese replaced the legendary Swiss. When micro-electronics and sophisticated communication gear were married to aircrafts in the last decades of the 20th century, their efficiency, navigation, capacity, safety, and maintenance improved. Further improvements are on the way with aircraft-parts made of composites. In the past 'convergence' had a different connotation. Now, it has a unique aspiration that is quite different from its past meaning—to create things starting with an atom or a molecule, and handling them one at a time. Therefore, an atomic scientist may have to teach a mechanical engineer on how to create a nano-machine, or work with a physician to produce a diabetic-tattoo, or collaborate with a microprocessor designer to invent a quantum-computing device. Thus, in the present times, to a large extent, 'convergence' means bringing multi-disciplinary teams under one roof so as to imitate Nature in solving problems, and to create advanced technologies that create superior products, just like how Nature does. Innovation must be inspired by Nature.

Engineers developed their manufacturing processes by physics and chemistry (furnaces, kilns, boilers, reactors, centrifuges, separators, evaporators, driers); by material casting (sand-casting, investment-casting, centrifugal-casting, die-casting, injection-molding); by material removal (For example, metal removal by cutting, turning (on a lathe), drilling, milling, CNC machining, planning, shaping, grinding, deburring, broaching, exploding, imploding); by material joining (welding processes); by material squeezing (forging, hammering, drawing, bending, crimping); by spinning and weaving (textiles); by layering (rapid prototyping, electroplating, printing); by etching (lithography) and by understanding the some basic laws of Nature (energy creation by hydel, wind, solar, tidal, thermal, nuclear technologies). By these processes engineers create things that run the wheels of the modern civilization—be it a building or a bridge, an automobile or a microprocessor, a solar cell or a nuclear reactor, a local area network or the internet. But take a note: All our manufacturing processes, until now, are gross and crude manipulation of materials. The present-day engineers do not have adequate knowhow to manufacture anything by manipulating the materials at micro-level. At this point in time, engineers realized that the old *heat-beat-treat* manufacturing methods are outmoded.

In Nature, all creation happens at either atomic level, or molecular level—at well below the nano scale. An egg is manufactured in a bird's belly by a process that begins with a microscopic cell. A cow manufactures milk from grass, by handling '*molecules*' of grass and other chemicals that ooze within its body. A tree encrypts its own blue-print within its tiny seed, in its DNA. A leaf manipulates—using sunlight—a few molecules of carbon dioxide and water to give a vital molecule of glucose which when bundled up gives variety of food stuffs. Some mollusks such as Abalone manufacture their shells—bonding molecules to molecules and building layers upon layers—which are stronger than the best ceramics man has ever produced. The tiniest factory in the Universe is the living cell, which is also the most complex—because it creates its own copy to support and renew a living being. Doubtlessly, all these are manufacturing processes of Nature by Nature. They transpire at atomic or molecular level, and they happen under the screen of thick darkness, impenetrable by the normal senses, and ununderstandable even to the best minds. Through *Biomimetics*, by probing the Nature more deeply, the scientific community is beginning to learn new technological tricks.

This is not the first time engineers are seeking Nature's counsel. Throughout the history, as everyone is aware, scientists and engineers have been stimulated by Nature. A bird gave wings to the man's imagination that led to the invention of aircrafts. Fish inspired the development of ships and submarines. Starry skies mystified Newton and Einstein who gave us the laws of universal gravitation and relativity, with which we could land on the Moon, and send a probe to a distant planet. Chromatic-eyes of a Balloon-fish fired-up a scientist's imagination to invent photochromatic lenses. Cockleburs of a bushy plant led to Velcro. The hoofs of mountain goats gave clues to rugged-but-flexible shoes. A spider's silk was the model for DuPont's Kevlar. Now, again it is chosen as a standard for developing renewable raw materials—after all, a spider can eat a part of its old web to make a new one. A Bombardier beetle's chemical gun is lending its secrets to create super-efficient chemical reactors. A gravity-defying Gecko is the latest '*model*' for developing new adhesives. Our immune system fueled the thought of anti-virus programs and fire-walls. Learning algorithms, expert systems, natural language processing, and artificial neural-networks are the technological babies of the brain's working mechanisms. The list can go on to another 100 pages. But the point is this: Nature has been inspiring man to achieve more perfection in his creations, by demonstrating her models, and acting as his mentor.

Seventeenth and eighteenth centuries constitute the golden period of mathematics with the astounding contributions from Descartes, Bernoulli, DeMovire, Newton, Leibnitz, Laplace, Gauss, Euler, Fermat, Fourier, Cauchy, Legrange, d'Alambert et al. The period 1870-1920 was the best for mechanical engineering with the improvements in steam engines, invention of IC engines, automobiles, moving assembly-lines etc. Three decades between 1900-30 are the years that shook physics with the discoveries of relativity, quantum mechanics, photo-electric effect, atomic energy, anti-matter, and so on. This century, the 21st century belongs to nano-technology, bio-technology, clean-energy technologies, stem-cell research, genetic engineering, virtual worlds, vertical transportation, and quantum computing. Progress towards useful end-products in all these futuristic technologies will be possible only by 'convergence' of dissimilar fields of research with an intense focus on Nature's sagacity.

In the recent years, many research fields have been spawned by scientists and engineers to explore, understand, and mimic Nature's design and Her manufacturing prowess. For instance, engineers are working hard at nanotechnology (the focus of this lecture) in labs with a goal to manipulate materials at the microscopic levels. Tools such as Scanning Tunneling Microscope (STM, for which physics Nobel prize was awarded in 1986), Atomic Force Microscopy, Magnetic Force Microscopy, Laser Spectroscopy, X-ray Lithography, Blue-lasers are enabling engineers probe deeper into the tiniest objects and create new solutions and products of the nano-scale. However, the first use of the distinguishing concepts of 'nanotechnology' (but predating use of that name) was in "*There's Plenty of Room at the Bottom*", a talk given by physicist Nobel Laureate **Richard Feynman** at an American Physical Society meeting at Caltech on December 29, 1959. Feynman described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally smaller set, so on down to the needed scale. In the course of this, he noted, scaling issues would arise from the changing magnitude of various physical phenomena: gravity would become less important, surface tension and "Van der Waal" forces would become more important, etc. This basic idea appears feasible, and exponential assembly enhanced by parallelism facilitates manufacturing of useful end-products. The term "nanotechnology" was defined by Tokyo Science University professor **Norio Taniguchi** in a 1974 research paper as: *"'Nano-technology' mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule"*.

To make nanotechnology practical, one may need teams consisting of atomic scientists, molecular biologists, genetic engineers, mathematicians, computer scientists, mechanical engineers, electrical engineers, chemical engineers, instrumentation engineers, physicists, physicians, neuro scientists, cardiologists, and even economists. In the present times, 'nanotechnology' is one of the best examples to illustrate the concept of "convergence of technologies". Again, 'nanotechnology' is not a single field of research, but a smorgasbord of technologies. Under its grand umbrella, it has many research areas such as nano-materials, nano-machines, nano-manufacturing, nano-lithography, nano-sensors, nano-circuits, nano-robotics, nano-fuels, nano-batteries, nano-medicine, nano-ethics (social issues of nanotechnology) each field with its own ambitious research agenda. It is forecasted that it will take atleast another five decades to experience the products of these technologies. Fifty years elapsed since Feynman first mooted this idea. It's been more than 20 years since STM was invented (by which individual atoms could be manipulated), with no significant end-products in sight. Alas, Nature doesn't lend its secrets that easily and that quickly! But, patience and persistence will pay off! Nature's delays are not denials.

This lecture will cover technologies related to motors, locomotion, food production, information storage and processing, repair, maintenance, recycling, emotions, aesthetics for the purpose of comparing human designs with Nature's designs. The most advanced technologies of today are only primitive when compared to Nature's. This lecture will prove one point: ***"All human science and technology, even the state-of-the-art, is only a pale imitation of Nature's technologies"***.

This lecture will give an overview of the Nature's benchmarks, and show how scientists and engineers all over the world are trying to imitate Nature. An overview of new tools invented and yet to be invented through research into nanotechnology will be covered (lecture will not address bio-technology, clean-energy, stem-cell research, virtual worlds, vertical transportation and quantum computing). The new fields such as nanotechnology will take atleast another couple of decades to become practical and useful to the general public, even at a low scale. To make that a reality, scientists and engineers are at work, taking cues from Nature. They are turning to ***Mother Nature—the Master Engineer,*** for advice, guidance, vision, strategy, inspiration, and help—the wisest step in an attempt to advance the technology further for the benefit of the mankind.

For Further Study:

1. Felix Paturi: ***Nature, The Mother of Invention—The Engineering of Plant Life,*** Harper & Row, 1976 (Book).
2. Janine Banyus: ***Biomimicry—Innovation Inspired by Nature,*** Harper Perennial, 2002 (Book)
3. Eric Drexler: ***Engines of Creation***, Anchor Books, 1986 (Book).
4. Scientific American (Sandy Fritz and Michael Roukes): ***Understanding Nanotechnology,*** Warner Books, 2002 (Book).
5. Deb Newberry, and Jack Uldrich: ***The Next Big Thing Is Really Small: How Nanotechnology Will Change the Future of Your Business*, **Random House, 2003 (Book).
6. ***The Shape of Life*** (Eight Part TV Program Transmitted on PBS, USA).
7. ***Engineering Marvels*** (Seven Part TV Program on History Channel).
8. **ISN** (Institute of Soldier Nanotechnology) at MIT, Boston: www.mit.edu
9. **Movie Clips of Toyota Robots:** www.toyota.co.jp/en/special/robot/
10. **"Accelerating Future" Website:** www.acceleratingfuture.com
11. **About STM:** http://nobelprize.org/educational_games/physics/microscopes/scanning
12. **BBC TV Programs:** *Human Body, Human Brain, Human Senses, Human Mind, Super Senses, Living Planet, Life on Earth, Trials of Life, The Secret Life of Plants, Life of Mammals, Life of Birds, Blue Planet, Life in the Freezer, The Secrets of DNA, The Origins of Life*.

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