Buckminster Fuller and his Fabulous Designs

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Richard Buckminster Fuller was an American designer who created fantastic designs. His non-conformist creative design ability was augmented with an urge to realize the prototypes not only for practical demonstration but also for widespread use. His creations called for new vocabulary such as synergy, tensegrity, Dymaxion, and the eponymous Fullerene. He had a design science philosophy of his own. He thought beyond the design of artifacts. He strived for sustainable living in the global world long before these concepts became important for the world to deal with. He is described as a comprehensive anticipatory design scientist. In this article, only his physical design artifacts that include two of his lasting design contributions, namely, the tensegrity structures and the geodesic domes are discussed.

Good designs bring a positive change in the world and the way we live. And great designs remain unchanged for decades, or even centuries, because nothing greater came along after them. Although everyone enjoys the benefits of good designs, the process of design itself is not understood by many because designing is an intensely creative and intellectual activity. Most often, great designs appear to be realized as a flash of an idea, a radical new thought, and a figment of the imagination of a gifted thinker. In reality, good designs, like great discoveries, come about as a result of sustained thought by creative designers who want to improve the environment around them and help change the world they live in. Buckminster Fuller was one such designer. His designs were fabulous. He thought what others did not dare think. He sought design solutions that were superior to everything else. No problem was insignificant to him, nor any problem unsolvable. He thought deeply about household cleaning chores, plumbing, driving a car, perception of size and distance in a world map, and other mundane problems. He also contemplated buildings

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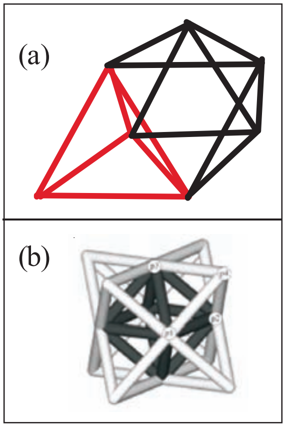
that can be flown, cars that can traverse on land, water, and air, and such concepts as practical applications of Einstein's theories of relativity. Almost everything was a design problem for him.

Early Designs

Richard Buckminster Fuller was born on July 12, 1895, in Milton near Boston in the United States of America, to a family of highly accomplished non-conformists. All the Fuller men studied at Harvard University. The unusual middle name, Buckminster, was an ancestral family name. As a child, Richard Buckminster Fuller tried numerous variations of his name. He used to sign his name differently each year in the guest register of his family summer vacation home at Bear Island, Maine. He finally settled on R. Buckminster Fuller [1]. But everyone called him Bucky, a name by which he preferred to be addressed and a name immortalized in buckyballs, as the C_{60}-fullerene molecules are sometimes called.

Bucky, who was born with acute myopia that remained undiagnosed in the early years of his childhood, developed great skills of touch and smell as all shapes appeared fuzzy to his imperfect eyes. When he was not even five years old, he surprised his kindergarten teacher by creating an unusually stiff truss built using toothpicks and dried peas. While the other kids in his class made structural models that had 90° corners just like what they had seen around, Bucky showed his non-conformist trait by opting for acute angles. His truss had triangles rather than squares and rectangles. More than 60 years later, Bucky patented his invention as an octet truss, which is widely used in space frames today. An octet truss consists of a tetrahedron sitting on a face of an octahedron, both of which are made using struts – not unlike Bucky's kindergarten model made with toothpicks stuck in the holes of dried peas. *Figure* 1a shows the elementary octet truss and *Figure* 1b shows the building block of a modern lattice material pursued for its high stiffness and strength [2]. This space-filling building block was Bucky's first inventive design.

Figure 1. (a) Building block of an octet truss comprising a tetrahedron and an octahedron. (b) A modern version of a lattice building block with which structures of high stiffness and strength can be built [2]. The central dark portion is an octahedron that is surrounded by eight tetrahedrons.



His second invention came soon after. As a boy, living on an island

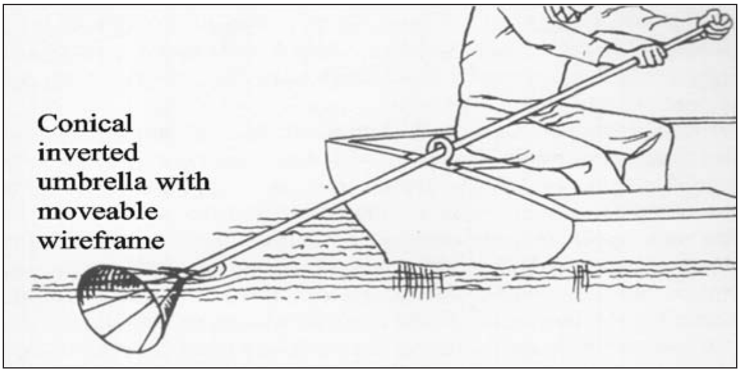


Figure 2. Mechanical jellyfish oar that the young Buckminster Fuller designed and used (adapted from [1]).

during summers, he observed Nature with keen interest. He interacted with sailors and fishermen and took great interest in their tools. During that period, he designed an unusual oar that was modeled after a jellyfish (*Figure* 2). It had fabric attached to a conical wireframe that was fastened to a long pole. Sitting at the back of the boat, as he pulled on the pole that was dragged behind the boat, the 'inverted umbrella', with its tip pointed towards the boat, offered little resistance. But when he pushed it, the frame opened and offered as much resistance as he would feel when he hit the ground with an oar. This contraption reduced his effort in propelling the boat. Furthermore, he was able to face the front and plan his maneuvers rather than with the conventional oar that requires facing the rear. This early boyhood design also exhibits the ease of use and comfort which are hallmarks of Fuller's designs.

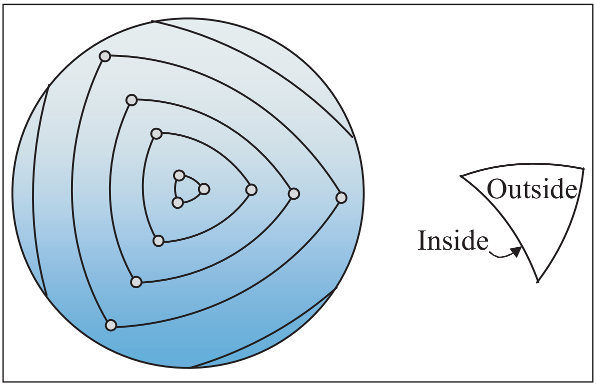
Bucky had asked his geometry teacher how points, lines, and planes, all of which are said to occupy no space at all, can create volumes that occupy space.

In his high school years, Bucky realized that his non-conformist inquisitiveness angered his teachers and decided to remain quiet. He had asked his geometry teacher how points, lines, and planes, all of which are said to occupy no space at all, can create volumes that occupy space. Snubbed by his teacher for his brashness, he learnt to keep his questions to himself and started to think deeply about them. This restrained behavior was let loose when he entered Harvard University. He was expelled in the middle of his course there. His family sent him to work at an upcoming Canadian textile mill as a punishment. Bucky used that opportunity to learn about modern machines that came from continental Europe and England. He showed his ingenuity in repairing and re-designing parts of the machines endearing himself to the workers and engineers there. Upon returning to Harvard, his slapdash behavior did not change and he got expelled for a second time. That was the end of his formal education. Rather than feeling sad, he felt liberated because he did not like to be bound by traditions.

Designing his Own Life

Fuller believed in experiential education rather than formal education [1]. His thought processes were esoteric even with such seemingly simple concepts as definitions of sine and cosine of an angle. He did not believe in flat triangles and hence was uncomfortable with the traditional definitions taught in his school years. Much later, when he studied spherical trigonometry, he thought that he understood the real meaning of those ratios. He had to experience a concept to understand it fully. As an adult, he would ask a child to draw a triangle on the ground with a stick. When the unsuspecting child drew a triangle, he would say that the child had drawn four triangles and not one. His abstruse explanation was that the real triangle as drawn lies on a sphere, the Earth. Then, there is another triangle that is the remainder of the surface of the Earth because that large triangle is also enclosed by three arcs just as the small one. He would suggest a thought experiment of enlarging the drawn triangle until the remainder of the Earth starts looking like a small triangle. For the third and fourth, he would point to the concave (interior) faces of the first two triangles (*Figure* 3). This four-triangle concept remained with him throughout his life. A tetrahedron with its four triangles figured in many of his designs.

Figure 3. Imagining four triangles when we draw only one triangle on the Earth.



Like all young men of his time, Fuller too wanted to take part in the First World War. His request was turned down the first time because of his poor eyesight. He then used a clever plan of using one of the boats accessible to him as a patrol boat and got himself an opportunity. His inventive mind became useful in rescuing pilots whose planes often crashed into the sea because of the immature flight technology of that time. After some failed attempts at improving the ejection seat, Bucky hit upon an alternative idea of pulling the whole plane out along with the pilot within two minutes of a crash. He designed a winch-like mechanism with a long rope that could be deployed quickly. His design saved the lives of some pilots. This success earned him an opportunity to be trained as an officer at the US Naval Academy. Bucky used this opportunity to learn a lot of technology of weaponry, strategic problem solving, manufacturing, and materials. He put all this experience to good use when he constructed models of his designs much later in his life.

Bucky married Anne Hewlett, the daughter of an architect James Munroe Hewlett. Their first daughter succumbed to a childhood illness and it was a major psychological blow for Bucky who also lost his job. His father-in-law, who had invented a new type of construction brick, asked Bucky to help. Bucky rose to the occasion and developed a new design and a technology to make the bricks. The bricks did not need mortar but used concrete pillars that supported them. This was achieved with holes present in the bricks into which concrete was poured as the bricks were laid (see *Figure* 4). To make the bricks light and cost-effective, Bucky explored alternative materials. He used shredded wheat bonded with magnesium oxychloride cement [1]. His bricks weighed so little that they could be tossed up easily during

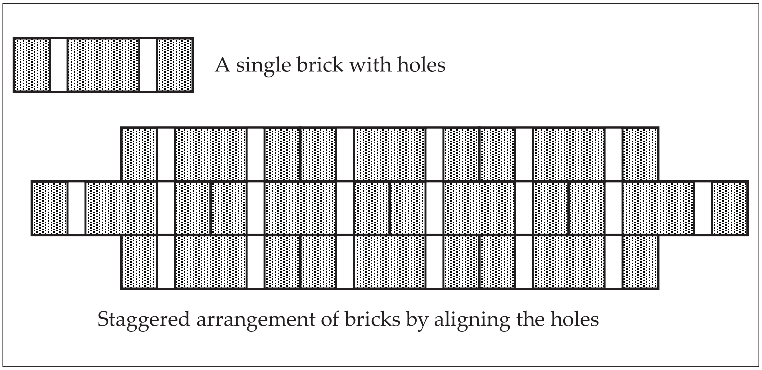


Figure 4. Schematic of a wall built with Fuller's bricks that had holes. Concrete was poured into the holes as the wall was built to create concrete pillars. Mortar was not needed in this construction method.

construction. Yet they were strong. They were also fireproof and non-absorbent. This led to the creation of a company by name Stockade Building Systems with the support of Bucky's father-in-law. This unusual construction technology met with much resistance from builders and architects. It was a lesson for Bucky: great technology is not easily embraced by the tradition-bound society. Financial difficulties forced Hewlett to sell his stocks and Stockade was sold to an insensitive company that promptly fired Bucky. This sent him into depression. He was 32-years old then.

According to Bucky, "a man can make sense or make money". He came to the conclusion that a thinking individual can contribute much more than a big corporation or an organization.

Bucky turned to spirituality for solace from his personal problems. His thinking turned metaphysical. A few years before that, he had believed that he could telepathically communicate with his first daughter, Alexandra, who had died as a child. When he felt he was pushed to a corner, he even considered ending his life in the autumn of 1927. In a surrealistic incident, which he narrated in his talks years later, he apparently had heard a voice that urged him "to apply himself to converting his experiences to the highest advantage of others" [3]. After this alleged supernatural experience, he conditioned his thoughts and aspirations and began to design his own life. He started to believe in the existence of Universal Intelligence. He thought that Nature's perfect designs and orderliness would not have been possible without the existence of the Greater Intellect.

Bucky's metaphysical thinking started to lean towards idealistic philosophy. He thought that he should serve humanity and not worry about earning a living. According to him, "a man can make sense or make money" [1]. He came to the conclusion that a thinking individual can contribute much more than a big corporation or an organization. He remained silent for two years and was engaged in deep thought. During those two years, he talked, and that too very little, only with his wife and second daughter, Allegra. He also decided not to consciously try to derive monetary benefits out of his ideas and inventions because he thought that the 'regenerative universe' always supports the required actions and would provide him indirect assistance. His faithful

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wife, Anne, supported his decisions despite her own skepticism. Bucky began to observe abstract patterns in everything around him and sowed the seeds of his dominant creative ideas of synergy and pattern integrity.

Design Thinking

During the two years of his self-imposed solitude, Bucky turned his attention to writing and sketching. He thought that he could convey his ideology and thoughts to the world only if he made them tangible. He kept a detailed account of his experiences, ideas, observations and designs. He wrote more than 2000 pages during this time. He jotted down whatever thoughts that occurred to him. He continued this practice even later. His collected diaries are known as a chronolife. He also imagined many kinds of designs. Some, for that time, were esoteric and some remain so even now. One day, he thought that it would be nice to control the opening and closing of doors with a simple hand-gesture. He imagined a beam of light interrupted by a hand which could do this. He wrote to his brother, Walcott, who was then working for General Electric. Walcott thought that GE would not waste its time doing such preposterous things. A few years later, he sent a telegram to Bucky saying that GE had the technology that could do just that. In another similar incident, Bucky told engineers at the Aluminum Corporation of America (Alcoa) that aluminum was a good metal to use in construction. The Alcoa engineers laughed at him and said that there were only two kinds of aluminium, soft and softer [1]. Years later, they appreciated what Bucky had meant.

Fuller was obsessed with the world map and the globe. He visualized the entire world as a global town. He imagined a world where people could travel fast from one place to another by air. Based on the upcoming commercial flight technology of that time, he thought that medium-range flights would be necessary to go across the continents with stopovers in between. He thought that a plane would have intermediate ports in uninhabited places such as Greenland or the Sahara desert. So, he started to design

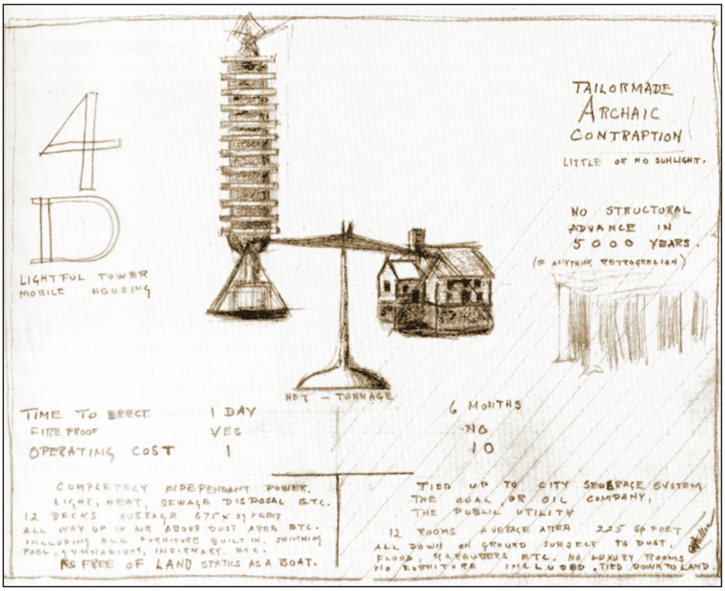
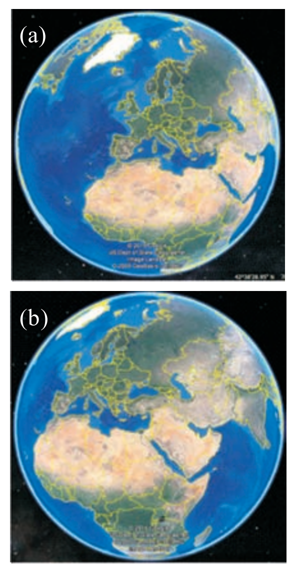


Figure 5. Decked tents that can be flown and installed anywhere as envisioned by Fuller.

easily erectable tents that depended on wind and solar energy for power (see *Figure* 5). He drew elaborate sketches that showed how the plane would drop a small bomb to make a deep hole into which the foundation of the tent got inserted. The workers would then secure the tent that would drop down from the plane. Such grand ideas got embellished later in his life and some turned into practical applications that Bucky himself conceived.

Fuller described the planet we inhabit as the Spaceship Earth. He wanted to identify the vantage point from which most of the landmass of the world can be seen from space. He concluded that the French Riviera is that point. If one looks at the Earth from a point directly above the French Riviera, most of the continents can be seen. Today, we can easily check this using Google Earth (www.google.com/earth), as can be seen in *Figure* 6a. This is debatable as can be seen in *Figure* 6b where a little more landmass covering entire Africa, almost all of Europe and Asia can be seen. Anyway, for Bucky, at that time, the French Riviera appeared to be the center of the most landmass of the world. This did not surprise him. In fact, he thought that it was natural because most powerful business tycoons chose to vacation at the French Riviera and made their connections. For Bucky, who had thought much

Figure 6. (a) A view of the earth as seen from right above the French Riviera – a place from where most of the landmass of the globe can be seen according to Fuller. (b) Better view of the Earth from another place showing more of the continents than in (a).



about global connectivity, this was not a coincidence but a natural consequence of universal connectedness. Although his conclusion is open to question, his thinking regarding the Earth and its map did lead to something practically useful, especially in today's global world (*Box* 1).

Box 1. Dymaxion Projection and Energy Grid

Drawing the world accurately on a two-dimensional plane (*Figure* A) is a challenge because a sphere is not a developable surface. Traditionally, we use a Mercator projection to draw the world map. Imagine a thin cylindrical shell around the globe on to which the world is projected. Then, the portion near the equator projects accurately, whereas, the portions farther from the equator get distorted and stretched. The poles do not get projected at all and the portions near the poles become unusually large. On the globe and in reality, Greenland is about one third of Brazil in terms of area. On the other hand (see *Figure* A), it looks three times bigger than Brazil. Another consequence of this traditional projection is that we are misled by the distances between continents and countries. This bothered Bucky.

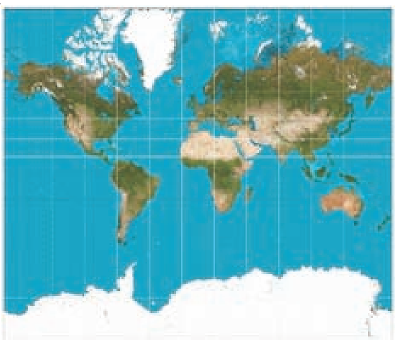


Figure A. The traditional world-map using Mercator's projection; the distortion in size and shape increases as we move farther from the equator. (http://en.wikipedia.org/wiki/Mercator_projection)

Bucky first imagined dividing the surface of the Earth into 20 equal spherical triangles in which the edges are circular arcs. At this point, there is no distortion but it is still not developable. So, he imagined an icosahedron (*Figure* B (i)) by replacing each spherical triangle with a plane triangle. The images of the landmass and water bodies of the Earth were then projected onto the 20 faces of the icosahedrons which could then be developed into a flat map. This map has very little distortion. By using a polyhedron with more faces than 20, the accuracy improves. Interested readers can see an animation of this projection at: http://en.wikipedia.org/wiki/Dymaxion_map#mediaviewer/File:Dymaxion_2003_animation _small1.gif.

Bucky went further than projecting the Earth's surface onto an icosahedron. He realized that there were many, many ways to open up and develop an icosahedron. He looked at two interesting ways, one in which the entire landmass appears like a single island with oceans surrounding it as a single large water body, as shown in Figures B(ii, iii), and the other where the world looks like separated islands. He called it the Dymaxion projection. This can be viewed as the pictorial portrayal of the old Indian adage '*vasudhaiva kutumbakam*' (*vasudha* = Earth or the world; *eva* = indeed; *kutumbakam* = family) that means the world is indeed one family.

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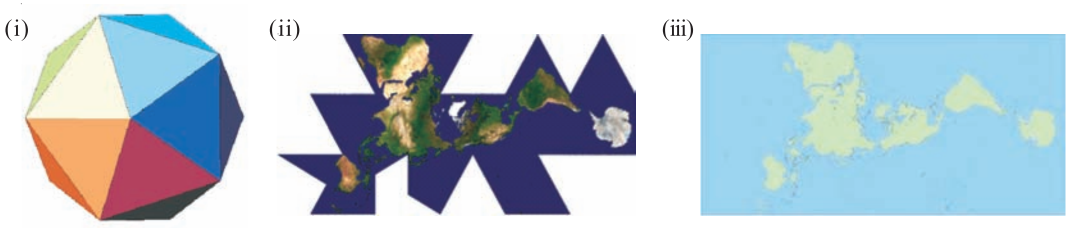

Figure B. (i) An icosahedron with 20 faces, (ii) the surface of the Earth projected onto an icosahedron and developed in a particular way, (iii) Dymaxion projection of the Earth where the entire world looks like an island in a great ocean.

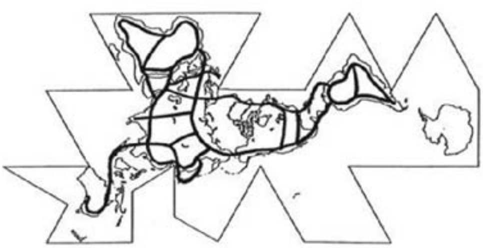

Figure C. Fuller's energy grid for the world in his Dymaxion projection.
© 1938, Buckminster Fuller Institute, Los Angeles

Bucky used his Dymaxion projection to think about big problems such as transportation, global business, communications, and power transmission. He drew a particularly interesting sketch, the energy grid shown in *Figure* C. He envisioned a single energy grid for the entire world. His grid takes into account the day and night hemispheres and connects the continents optimally. He thought that world peace and harmonious economic development are possible when we look at the world in this manner. His vision is yet to be realized.

Designs for Homes

During his troubled years, Bucky could not afford a good place to live. So, his thoughts naturally turned towards shelter. It had also dawned upon him that he would have the most impact only if he treaded a path that was different from the current and known practices in housing design.

It is well known that the area enclosed by a closed planar curve of a given length is maximum if the curve is a circle. It is also known that building walls is a major component of cost in the construction of a building. Why is it then that we do not build circular buildings but opt for rectangular ones? It may be because of the relative ease of building rectangular walls rather than circular ones. Or, it may well be that we follow the tradition. But it was not so for Buckminster Fuller, the non-conformist. He took the less trodden path and it made all the difference.

Bucky argued that "affordable housing is an innate human right". He realized that he could not solve the socio-economic problems. But he was convinced that he could solve the problem only if his designs were perfect and were not affected by the existing external environment.

Bucky's house would cost just as much as a car at that time. It was autonomous and transportable just a like a car. Its power sources were the wind and the Sun. It had rain-water harvesting and facility for recycling water. Isn't this what we are talking about today?

Bucky's imagination started with what he called a 4D house (*Figure* 5). The fourth dimension was perhaps his own abstract dimension. He wanted a house to be able to relocate easily, perhaps by flying it using a zeppelin (a dirigible airship) or the modern-day blimp. It was a futuristic thought process that even the 2009 animated movie *Up* did not match. In *Up*, the house is carried by a hot-air balloon but the house is still of the traditional construction. Fuller's imagination in the late 1920s and its practical realization a few years later was much different. He was able to pack a house in a large suitcase. It could be moved, relocated, and re-assembled just like re-planting a tree. This was wild imagination, but its manifestation into reality was not too far. And it had more.

When Bucky had been silent for two years, as stated earlier, he had sketched his wild ideas on paper in a manner that was comprehensible to others. Word about these sketches spread, often explained by his wife, Anne, who became a spokesperson for him during that time. Bucky also wrote an elaborate book and made a 50-page booklet that he christened the *4D Time Lock*. He submitted this to the American Institute of Architects (AIA). This booklet explained how houses could be mass-produced just like automobiles. Bucky's house would cost just as much as a car at that time. It was autonomous and transportable just a like a car. Its power sources were the wind and the Sun. It had rain-water harvesting and facility for recycling water. Isn't this what we are talking about today? It had more. It had provision for packaging household solid waste – something the world has not yet attempted. In essence, Bucky had come up with a design for a house that did not depend on civic amenities of power, water, and sewage disposal. Since individuals cannot control them, Bucky's idea was to avoid using them. These radical ideas were summarily rejected by the AIA. The same organization gave its first architectural design award to Bucky a few decades later.

Bucky was not one to be disappointed when his ideas were rejected. In his two contemplative silent years, he had designed his thinking style that only sought perfect designs. And he waited for those who would understand and appreciate them. This came in the form of Marshall Field, a major department store in the United States at that time. Bucky was asked to display his 4D house in a new furniture store started by Marshall Field. A wordsmith was hired to change the name because '4D house' did not sound appealing to the company. With inputs from Bucky, a name was born – Dymaxion house. It is a combination of three words: *dy*namic, *max*imum, and *ion*. The importance of the first two words is clear: his houses would be able to move and they extracted the maximum out of everything. The third word 'ion' was to be a scientific word that lent credence to the radical new thought and design. Bucky liked this word so much that he adopted Dymaxion for many of his other inventions and creations in the years that followed.

The Dymaxion house was a complete house just like any other. It had a living room, kitchen, bedroom, bathroom, etc. The kitchen was a Dymaxion kitchen. The bathroom was a Dymaxion bathroom. To elaborate, a dymaxion bathroom can be installed in three hours anywhere. As shown in *Figure* 7, it had a toilet, a sink,

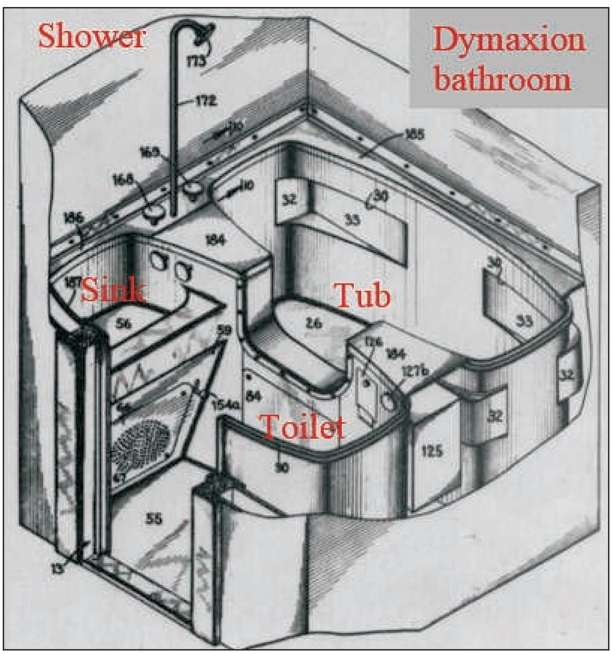

Figure 7. Dymaxion bathroom designed by Fuller could be quickly retrofitted anywhere.

a shower, and a tub. It was to be erected using four sections made of copper or aluminium (and later with a plastic material). It weighed only 200 kg and occupied a 5 ft × 5 ft footprint. It had many innovations too [2]. The sink had a side-hole rather than a central hole so that babies could be washed safely. To clean , Bucky had developed the concept of a fog-gun which had been inspired by his experience of heavy grease getting washed away by wind and mist in storms when he worked for the US Navy. The modern-day toilet found in passenger aircrafts is not too far from a Dymaxion bathroom. Bucky also developed a Dymaxion Deployment Unit (DDU) that helped install Dymaxion units easily.

To begin with, the Dymaxion house was circular in shape. It had a nearly conical roof with a spinning ventilator at the top. The floor was a few inches above the ground as the whole house was suspended. This led to natural ventilation that kept the house cooler than the outside. The roof hung from a central mast using cables. It had windows all around. It was to be constructed with the best materials available at that time. It could withstand tornado winds. Only two prototypes were built. Bucky himself lived in one of them, the Wichita House (*Figure* 8). Yet, we do not see Dymaxion houses today. It is a great story that sheds light on Bucky's changed personality as years passed.

During World War II and its aftermath, there was a dire need for economical houses that could be quickly erected. The powers that be thought of Bucky's Dymaxion house that he had conceived in

Figure 8. Wichita House, one of two prototypes built of the Dymaxion house.

the late 1920s. By then, Bucky was famous and in an influential position. While everyone wanted a simple pre-fabricated house, Bucky insisted that he would design and build a perfect house that could be installed anywhere in the world. He was able to convince Beech Aircraft in Wichita, Kansas, USA, and others involved in the decision to fund the execution of the project. The house began to take shape and two prototypes were completed even as Fuller Houses Inc. was founded. Investors and bankers came forward. Prospective residents, especially women, liked the prototype houses. Mass-production was planned. But Bucky became the impediment this time. He thought that the house needed to be perfected and pointed out one problem after another and delayed the mass-production and installation. He insisted that the best materials and processes be used. It dragged on even as the stock prices in Fuller Houses rose. Disagreements started to crop up between Bucky and Beech Aircraft. By then, people started to lose interest, investors sold the stocks, prices fell, and the Dymaxion house collapsed – financially and not structurally. Bucky did not seem to regret it and was gratified with the perfection he was able to achieve. Monetary benefits from his designs did not matter to him just as he had vowed at the beginning of his two silent years in the late 1920s. And his Dymaxion designs continued for years. His most important Dymaxion design after the house was the car.

Dymaxion Design of a Car

Fuller always dreamed of an omni-medium transportation vehicle – a car that could go on land, water, and air. While the latter two remained elusive in terms of practical application, the car for transportation on the land saw the light of the day. Bucky used many innovative concepts in designing his Dymaxion vehicle. It had three wheels; the front wheel had propulsion while one rear wheel had steering. He claimed that this was how fish swam. Observing ducks taking off and a pole-vaulter doing the jump, he came up with the concept of what he called jet stilts. Some of these were abstract design concepts not easily palatable from a scientific perspective. Some say that he foresaw the development

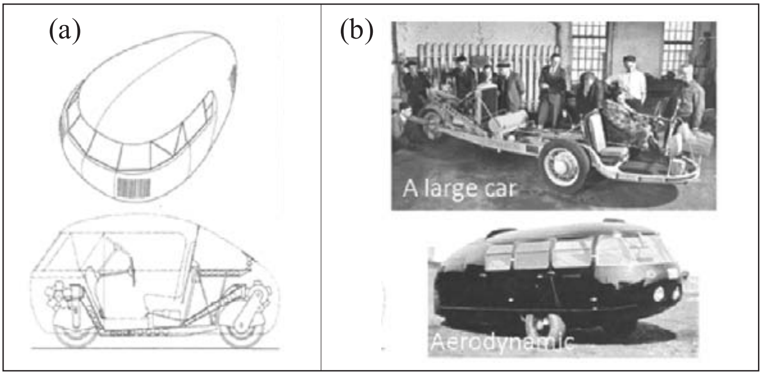

Figure 9. (a) Sketch of a Dymaxion car by Fuller.
(b) Photographs of a Dymaxion car.

of turbojet engines. These debatable claims notwithstanding, one should appreciate the practical realization of a Dymaxion car with some unique capabilities.

At an opportune time, Bucky recruited some of the best engineers, including Starling Burgess, the famous naval architect and a restless genius of American Design, just like Bucky himself. Like the Dymaxion house, the car was built with the finest materials available. The resultant Dymaxion vehicle was about 20 feet long. It could accommodate 11 passengers, gave 30 mpg (12.8 km/l) and could reach 120 mph (190 kmph). It was aerodynamic. The famous sculptor Isamo Noguchi had built its clay models for testing in wind-tunnels. It used a Ford V8 engine. It could make a 180° turn, unusual for a car even today. It could make a circle of 1 foot diameter making parking it easy. *Figure* 9a shows the schematic and *Figure* 9b, the photographs.

The car became a showpiece when it was displayed across the US. It was taken to Washington DC for Mrs Roosevelt, the wife of the erstwhile American President, to see. Walter Chrysler and Henry Ford (founders of two great American car manufacturing companies) too had praised this car. Chrysler, in particular, noted that the Dymaxion car came very close to the car he had thought of. However, bankers and stockholders who ran big corporations refused to back such a sophisticated and superior car. A good and durable car would have hindered the sale of new cars as sale of used cars increased. Therefore, the desire for a stable economy prevented new technical advances being used rightaway. While this was one reason why the Dymaxion car was not commercially produced, there were two other reasons. The first is a freak accident that killed two people. The other reason is that Bucky thought he was deceived by Henry Kaiser and Alexander Taub [1]. The Dymaxion car may yet see the light of the day sometime in the future as it is not technically flawed.

Lasting Designs of Buckminster Fuller

Two designs of Buckminster that captured the imagination of others and continue to influence people even today are the tensegrity structures and the geodesic domes.

Tensegrity Structural Designs

Although it is difficult to comprehend Bucky's abstract thought process, it is not hard to understand his concept of tensegrity, a portmanteau word that combines 'tension' and 'integrity'. A tensegrity structure comprises tension elements (taut cables) that can support compression elements (struts) wherein none of the struts touch each other but they support each other through the tension elements (*Figure* 10). Its amazing ability of supporting a much larger weight than the weight of just the structure stems from the tension that exists in the cables.

Bucky believed that tensional elements are the key to any good structure. If a tensegrity structure experiences loads that make the taut cables slack, the structure loses its stiffness and form. When

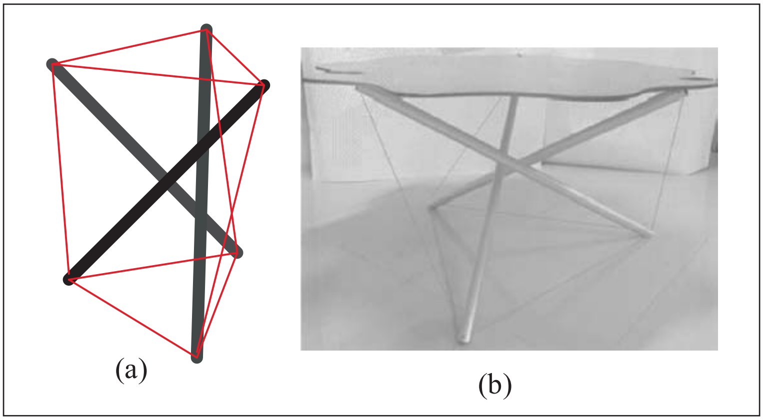

Figure 10. (a) Schematic of a tensegrity. Nine tensioned cables are connected to three rods. The resulting structure can support itself and retain its shape. (b) A practical tensegrity table built and kept in the author's laboratory. It clearly supports the weight of the glass top [4].

the loads are removed, it springs back to its original form as if it remembers. This is not magic. A tensegrity structure requires its cables be stretched when it is assembled. This stores elastic strain energy in it. A stable static equilibrium requires that this energy be at a minimum. So, the structure transitions to a configuration that has minimum energy. When a force is applied on a tensegrity structure, the minimum configuration shifts due to the additional work potential caused by the force; when the force is removed, it returns to the original minimum configuration. Hence, tensegrity structures are used in deployable devices such as space antennae and solar arrays that need to be tucked into small spaces and then deployed by removing the constraints.

Bucky described tensegrity as “islands of compression in an ocean of tension”. This notion can be seen in *Figure* 11. These structures were synthesized systematically using the mathematical tools of optimization [4]. The raw materials needed to build a tensegrity are cheap. But assembling and erecting them with pretension is hard.

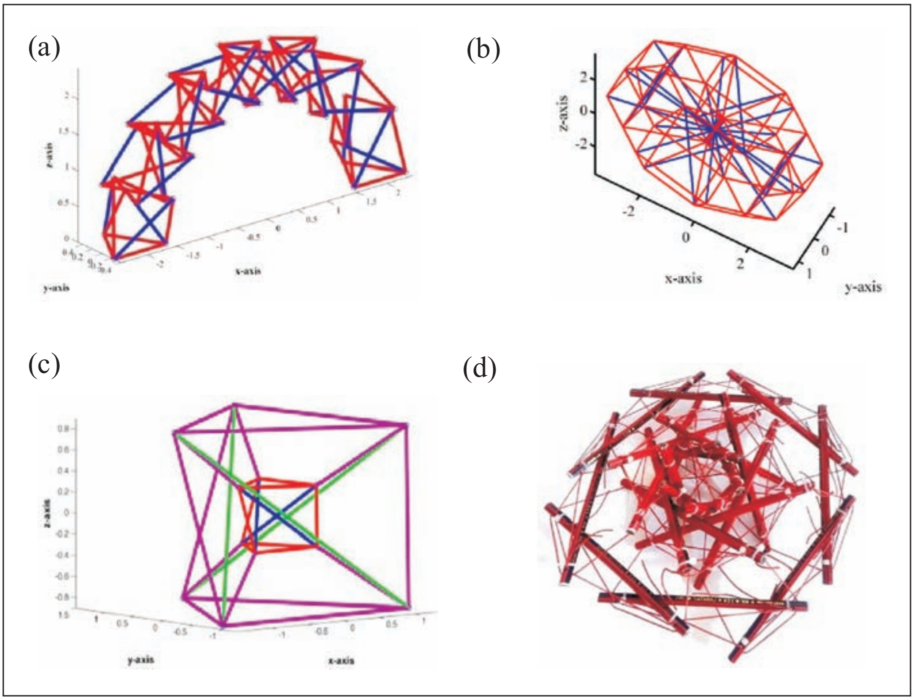

Figure 11. (a) A tensegrity arch. (b) A cytoskeletal model of a red blood cell showing the biconcave discoid seen in it. (c) A model of a cell with its nucleus – a tensegrity inside a tensegrity. (d) A prototype of the red blood cell tensegrity built using pencils and pieces of string [4].

One of the major applications of tensegrity structures is in art. Tall needle towers and large tensegrity structures with their nearly invisible tensioned cables amaze onlookers because the struts seem to be hanging in midair. Engineering applications are now emerging in deployable devices. One of the major insights of the tensegrity concept is that of Donald Ingber [5] who showed that a cytoskeleton – the skeletal network inside a living cell – is a tensegrity structure. The actin filaments (cables in tension) and microtubules (struts in compression) form a stiff and strong network that impart structural integrity to otherwise flexible cells. The ability to squeeze through vascular capillaries and regain the shape later is consistent with the deployable feature of tensegrity structures. Experiments have shown that if an actin filament is cut using a laser, the cell loses its shape and collapses. Some anti-cancer drugs disturb the microtubule network and make the cells lose their ability to divide. For tensegrity, it has been a long journey indeed, from artistic sculptures to cell biology.

Like Bucky, Snelson extended the concept of tensegrity far beyond a simple structure. Snelson finds tensegrity in origami, weaving patterns, magnetism, planetary systems, and quantum mechanics. His thoughts are truly aligned with those of Bucky where seemingly simple concepts are connected with profound bodies of knowledge.

It is pertinent to mention that Fuller and his student Kenneth Snelson fought over patenting the tensegrity concept. Snelson was a student at Black Mountain College in North Carolina, where Bucky lectured extensively. Snelson had shown Bucky an unusual structure that he had made using rigid crosses held together by tensioned cables. Bucky was overwhelmed by this and exclaimed that this was the concept he had in mind all along and that Snelson had built what he had envisioned. Biographers and students of Bucky acknowledge this and give due credit to Bucky for this invention just as the patent office did in 1962. Snelson's contribution is not to be ignored. Today, Kenneth Snelson maintains an informative web portal (http://kennethsnelson.net/tensegrity/) with a lot of insightful description of the concept of tensegrity and how to build tensegrities. Like Bucky, he extended the concept of tensegrity far beyond a simple structure. Snelson finds tensegrity in origami, weaving patterns, magnetism, planetary systems, and quantum mechanics. His thoughts are truly aligned with those of Bucky where seemingly simple concepts are connected with profound bodies of knowledge.

Geodesic Dome Designs

Fuller had used simple intuitive logic to conceptualize geodesic dome structures. Such a dome enclosed the most volume for a given surface area. Its footprint – a circle – enclosed the most area for a given perimeter, as is already mentioned. When a supersized tanker was doubled in size, it could carry eight times the cargo with only four times the material used for constructing it. Bucky applied this simple logic: you get more bang for the buck! The favorable surface-to-volume ratio means that the large thermal mass of air inside a dome did not need additional provision for thermal insulation. By extending his thinking a little further, Bucky also realized that such domes were also structurally stiffer and stronger than most other shapes. They were also efficient aerodynamically. He correlated aerodynamic efficiency to reduced heat loss. Heat loss was further reduced by concave interiors. Thus, the domes were naturally chilled. In fact, an uninsulated aluminum dome erected in Kumasi in Ghana was felt to be a bit too cold by the people who entered it when the Sun was scorching outside [6].

[1] A geodesic is the shortest-distance path between two points on a surface.

The aforementioned advantages can be found in domes of any shape. Why then a geodesic[1]? Buckminster Fuller had an intuitive explanation. He connected it with his Dymaxion projection of the Earth. He thought that Nature always does things in the most economical way [6]. Bucky reviewed his own old drawings of Dymaxion houses. He realized that the central mast got bigger and fatter as he increased the height of the tower. To him, the connections to the mast and the mast itself appeared to approach a geodesic. It was intuitive thinking again. He somehow knew that geodesic domes would give the best stiffness and strength for a given weight of the structure. Some of them proved to be strong enough to withstand storms and earthquakes.

A geodesic spherical dome can be thought of as a network of great circles crisscrossing each other on a sphere. One can imagine a set of triangles in such a network. These triangles can approximate the surface of a sphere. An icosahedron is one simple example. Starting with this simple idea, Bucky began to replace the triangles with different polygons and polyhedrons. Pentagons, hexagons, tetrahedrons, and octahedrons started to appear in his dome designs. A famous design comprising 20 hexagons and 12 pentgons is named after Bucky. It was found in the C_{60} molecule for which Robert Curl, Harold Kroto, and Richard Smalley were awarded the 1996 Nobel Prize in Chemistry. The C_{60} carbon molecule was christened a Fullerene or a Buckyball [7–9].

As with some great inventions, there is some controversy about whether Buckminster Fuller was the first to conceive geodesic domes. Walter Bauersfeld had built a planetarium dome for Zeiss Corporation in Jena, Germany, in 1922. Bucky was most likely aware of it. It is argued by Fuller's loyal supporters that Bauersfeld's design was coincidental and not a result of deep thought. Unlike Bucky, he did not use that design again. Bucky, on the other hand, studied geodesic domes in detail and designed several variants. He also developed techniques to build such domes. He recruited students to build the domes and got contracts to build them in different parts of the world. Most importantly, he patented it whereas Bauersfeld had not sought a patent giving credibility to the argument that Bauersfeld merely built one dome without much thought. Bucky founded a company Geodesics Inc. and popularized and continuously improved the domes. Some were used as pavilions for trade fairs and expositions and attracted more attention than the wares displayed under the dome. Some were used in radio telescopes. More than 200,000 domes have been built around the world [6]. See *Figure* 12 for one of the famous domes built from his designs. Bucky noted in an interview that but for the popularity of the geodesic domes, he would have remained known only to an esoteric few and not have become a celebrity.

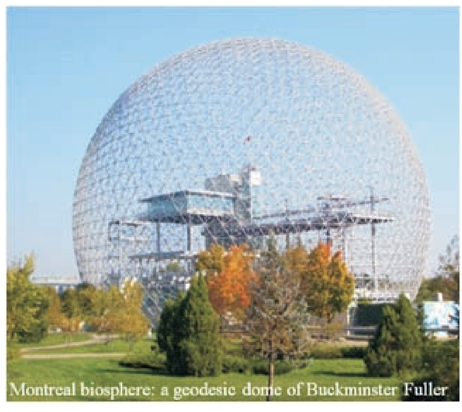

Figure 12. A recent picture of the Montreal biosphere; the original one was designed by Fuller for the United States pavilion for the World Expo in 1967.

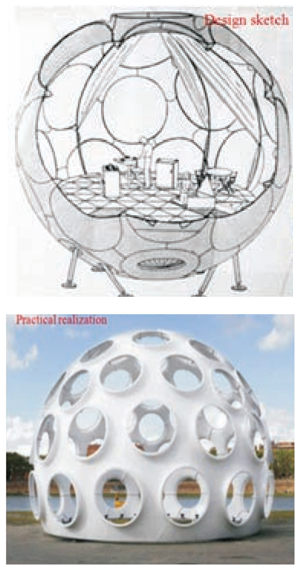

Figure 13. Fly's-eye dome: a mass-producible geodesic dome. The original sketch was meant to be a house but it is used as an artistic recreational structure today. This is equivalent to a geodesic dome made with polygonal panels but is much easier to mass-produce as cast pieces that can be assembled easily.

Geodesic domes had a few disadvantages too and Bucky was aware of them. He tried to address these issues and improved his designs. The domes were not suitable for certain environments, e.g., crowded urban spaces. Stacking them was difficult as compared to the usual rectangular buildings. All domes looked almost the same – mostly hemispherical or spherical – although any surface could be converted to a geodesic dome. They did not have good acoustic characteristics and suffered from echoes if sufficient care was not taken. Furthermore, any little sound could be heard anywhere in the dome. The same happened to odors and fires because they spread evenly and easily inside the dome. If domes were used for homes or office spaces, furniture had to be custom designed. While these problems could be addressed with some innovations, a nagging problem with the domes was leaks. With many pieces joined together, there was always the problem of gaps that were responsible for leaks. Even though stress was uniformly distributed, strain was not. Therefore, thermal expansion, imperfect manufacturing of the pieces, and improper assembly could cause uneven deformation in the domes. This called for sophisticated technology for fastening the pieces together. Out of these efforts came a new design called a fly's-eye dome (*Figure* 13). Here, instead of assembling the polygons, a pre-cast piece with a circular hole was designed. Imagine a sphere riddled with holes in a regular pattern. What is left is a shell that resembles a curved approximation of the triangular network. Today, we see domes that use pre-loaded struts, some of which are curved, that are used as foldable bags, baby-play domes, and mosquito-net domes. The domes are here to stay in various forms even if we may never build geodesic dwellings.

Design Science

Fuller thought that his grand designs were not conceived as a result of sudden revelations amidst random hit-or-miss trials which is the way we normally associate with inventors. Indeed, his great designs were a result of conscious thought sustained over a prolonged period. In 1927–1929, he had lived in silence and had contemplated on many things. As a result, he claimed, he

Box 2. Buckminster Fuller's Indian Connection

Buckminster Fuller had admired Mahathma Gandhi and had read his writings in his contemplative two years from around 1927–29 [1]. He had visited India for the first time in 1958 and had given three lectures in New Delhi. He had noticed that a "striking woman in a beautiful sari was given a seat of honor in the front row" [1] in all three lectures and that she was listening to him in rapt attention. She met him after the third lecture to know more about a model he had shown. That lady was Indira Gandhi. She invited Bucky to her home to meet Jawaharlal Nehru, the Prime Minister of India at that time. Both Nehru and Indira Gandhi were very impressed with Bucky's ideas and vision. He visited India several times later and had met Indira Gandhi again. Bucky had referred to Indira Gandhi as his friend in one of the interviews. According to an informal source on the Internet (http://fadesingh.tumblr.com/post/55849407168/), Indira Gandhi had introduced Bucky in a meeting, which shows how much insight she had into Bucky's contributions and way of thinking. Her words were:

"*We have with us today an unusual person, rather remarkable person. Mr. Fuller is described as an architect. He is that because of his intense concern with living space. But he's something more than an architect, because his obsession is with the architecture of the universe.*

We all have heard of Mr. Fuller's invention, the geodesic dome. It is now seen all over the world. It is a brilliant use of space and material. Then, the world map and other items. But what is far more important, Mr. Fuller has shown how to get the maximum from the minimum material by making the most intelligent use of the resources available on earth."

During one of his visits to India, Bucky had helped build a geodesic structure on the campus of Bengal Engineering College (now, Indian Institute of Engineering Science and Technology, Shibpur, West Bengal) *.

* Private communication with Prof. Amitabha Ghosh, currently at IIEST, Shibpur, West Bengal, India.

came up with the concept of synergy. For him, synergy was a concept that gave rise to new ideas when different elements were seen together rather than singly. This is somewhat akin to the modern complexity theory where new behavior emerges in a system which its constituents do not possess. His Dymaxion ideas, he often said, had synergy in them. He followed the sailor's credo: 'Everything in its place and a place for everything'. He organized his experiences and thoughts and sorted them as and when he needed to find a new idea. He defined 'thought' as "a relevant set of experiences bounded by macro-irrelevant and micro-irrelevant experiences that are temporarily separated inwardly and outwardly" [1]. This is consistent with his four-triangle thought experiment. With a real question on hand, he considered its complementary question and then took into account the other sides of those two questions. He thought that four is the minimum number of varieties of anything, be it experiences, faces of a geometric model, people, and anything else. According to him sorting through these four aspects of a problem helped him think clearly and find absolute solutions. He called his thought process Design Science. He argued that he abstracted the problem leaving all that was known about it behind and looked deep into it to find a comprehensive solution. He did not just preach this philosophy; he practiced it. After his major ideas of the Dymaxion house and the Dymaxion car were put to test and earned him recognition, he realized that he had to engage in conscious thought once again to come up with something that is more useful and pragmatic than synergy and the Dymaxion design. He did this again in 1947.

Starting from 1947, Bucky took time off from his usual busy schedule of talks and travels. He focused on finding something pragmatic to benefit humanity much more than his earlier inventions had done. It is said that he spent much of 1947 and 1948 studying spherical geometry and worked with great intensity. It was during that period that he came up with his geodesic dome and tensegrity theories which had been vague to him until then. By then, he was also older and wiser than in 1927. Both ideas did have the impact on society that he had sought.

For some gifted thinkers, their imagination ran much faster than they can realize their designs in practice. Charles Babbage is a good example [10]. Babbage would conceptualize a new mechanical computing machine even before he got the previous machine. His machines remained unrealized fully. Fuller was not like that in his main endeavours. He ensured that he followed up on his grand ideas. He played a major role in the construction of his designs. He learnt to build things as a child just as rigorously as he thought about things. He tried to see practical utility in everything. He had devoted three chapters in his book *Nine Chains to the Moon* to explain his interpretation of Einstein's theories of relativity and its practical applications. It is said that the publisher had reservations about these chapters and was reluctant to publish the book as Einstein himself had said that not many in the world understood his theories. Bucky was not disheartened and requested that Einstein's opinion be sought on that issue [1]. This was around 1936. To Bucky's surprise, a meeting was arranged between Albert Einstein and himself. Apparently, Einstein had read the manuscript of the book, appreciated Bucky's effort, and approved the inclusion of the chapters in the book saying, "Young man, you amaze me. I cannot conceive anything I have ever done as having the slightest practical applications… but you appear to have practical applications for it" [11]. This is a great compliment for a man who never got a formal degree.

Bucky's accomplishments were many in his long life that was well lived. He died on July 1, 1983. He was admired as a global thinker. His numerous talks and books inspired many architects, innovators, designers, and policy makers. This self-taught innovator received 47 honorary degrees even though he had not received a formal degree. He taught at major universities in USA such as Harvard and MIT as well as liberal colleges such as Black Mountain. He was on the cover story in the Time magazine in 1964. In 1983, he received the Medal of Freedom from President Ronald Reagan, the highest civilian award given by the United States government. He got honorary degrees from numerous institutions, toured the world as a celebrity speaker, wrote numerous books, and made significant contributions to the world by being a mere designer. He truly deserves the accolade of being called a comprehensive anticipatory design scientist. He put design science on a pedestal and let the world look at his designs in awe.

Suggested Reading

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