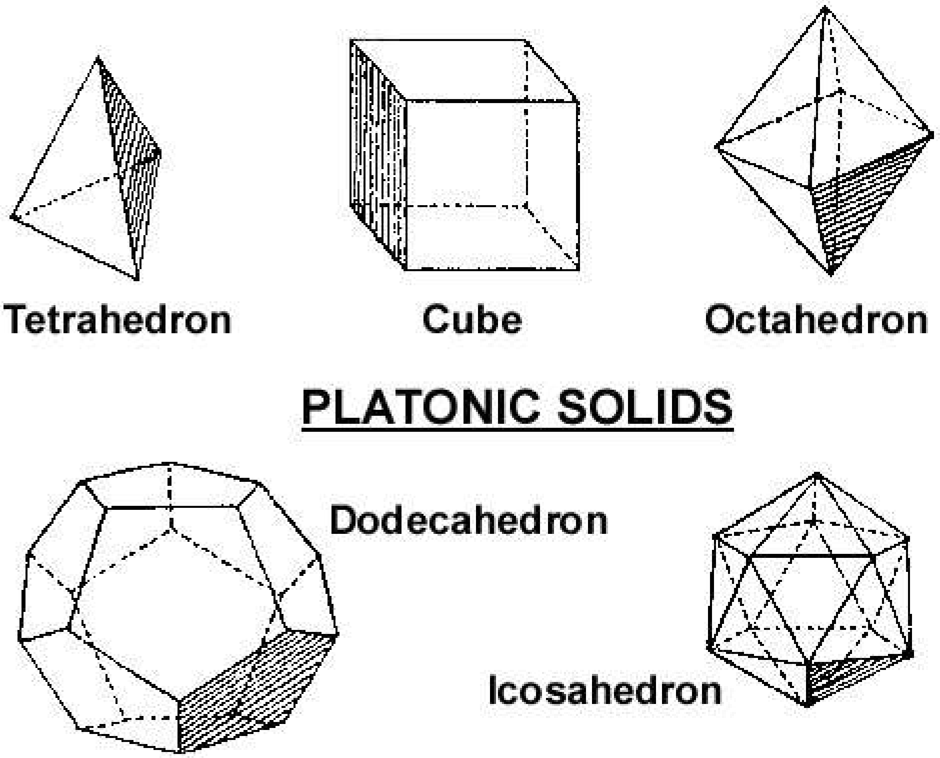
POLYHEDRAL STRUCTURES

By Prof. R. Jayaraman

A *Polyhedron* is a solid whose external faces are all polygons. A *Regular polyhedron* is a solid whose faces are all identical regular polygons. Regular polyhedrons are known as *Platonic solids*. The word polyhedra is also used for polyhedrons.

The Platonic solids:

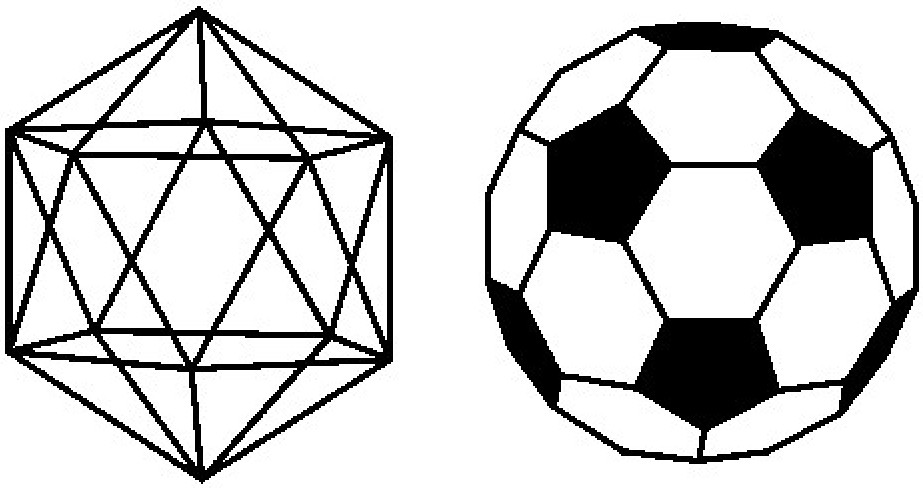
The Platonic solids are: The *Tetrahedron* consisting of 4 equilateral triangular faces; the *Cube* consisting of 6 square faces; the *Octahedron* consisting of 8 equilateral triangular faces; the *Dodecahedron* consisting of 12 pentagonal faces; and, the *Icosahedron* consisting of 20 equilateral triangular faces. The Greek philosopher Plato (427-347 BC), in his book *Timaeus*, associated these five Platonic solids with the five elements fire, earth, water, air, and space.



All the above solids can be inscribed in a sphere. Surprisingly, no other regular polyhedron exists.

The Truncated icosahedron:

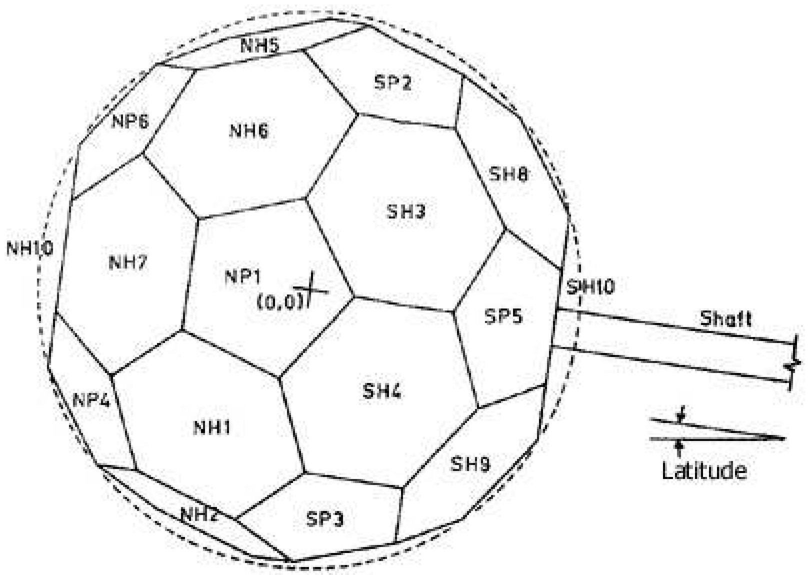
Many situations arise where we would like to approximate a sphere by a *closely-fitting polyhedron*. None of the Platonic solids is suitable for this application. Fortunately, there exists a 32-faced polyhedron known as the *Truncated icosahedron* or *Buckyball polyhedron* having 20 regular hexagons and 12 regular pentagons for its faces, whose shape approximates to that of a sphere, and which can be circumscribed by a sphere in a mathematically perfect manner. It is derived from an icosahedron by truncating each of its 12 vertices so that each vertex is replaced by a pentagon and each of the 20 former triangular faces is converted to a hexagon. See the Figures. The most familiar example of the use of the Buckyball polyhedron is in the manufacture of football. Leather pieces cut to the shapes of regular hexagons and regular pentagons are stitched together to make the football.



THE ICOSAHEDRON (at left) and
THE TRUNCATED ICOSAHEDRON

The significance of the Truncated icosahedron as a structural engineering form was first appreciated by the famous architect Buckminster Fuller (1895-1983), who popularized it for lightweight structural domes which he called *Geodesic domes*. Structural domes suspended from a network of steel or aluminium alloy members conforming to a truncated icosahedron have come to be known as *Fuller's domes*. Fuller's domes have been incorporated in planetariums, auditoriums, indoor stadiums, housing quarters and in other civil engineering structures. It has been estimated that, 300,000 Fuller's domes have been built so far.

The Star projector of a Planetarium is also shaped as a Buckyball polyhedron. The celestial sky is divided into 32 regions appropriate to the 32 faces of the polyhedron. The positions of the stars falling on each region are transferred to the corresponding face of the polyhedron. The star positions on the face are then inverted, and minute holes are drilled on the face to represent the stars. The polyhedron is illuminated on the interior, and the illuminated star holes are projected onto the planetarium dome by separate projectors placed over each face. Diurnal motion of the stars is reproduced by slowly rotating the polyhedron about a shaft that is oriented parallel to the polar axis of the earth. The Figure shows the Star projector of the Model Planetarium of 10 metres diameter, which was constructed in the College of Engineering, Trivandrum in 1976. The author was associated with this project.



32-FACED STAR PROJECTOR

Polyhedral crystals:

A crystal is defined as the polyhedral form, bounded by smooth faces, which is assumed by a chemical compound under the action of its intermolecular forces, as the substance changes its state from liquid or gas to solid. It is formed from a solution, or from molten or vapourised material. Crystals can also be grown artificially by suspending a small core crystal in a saturated solution of the material in a suitable solvent, and allowing it to evaporate.

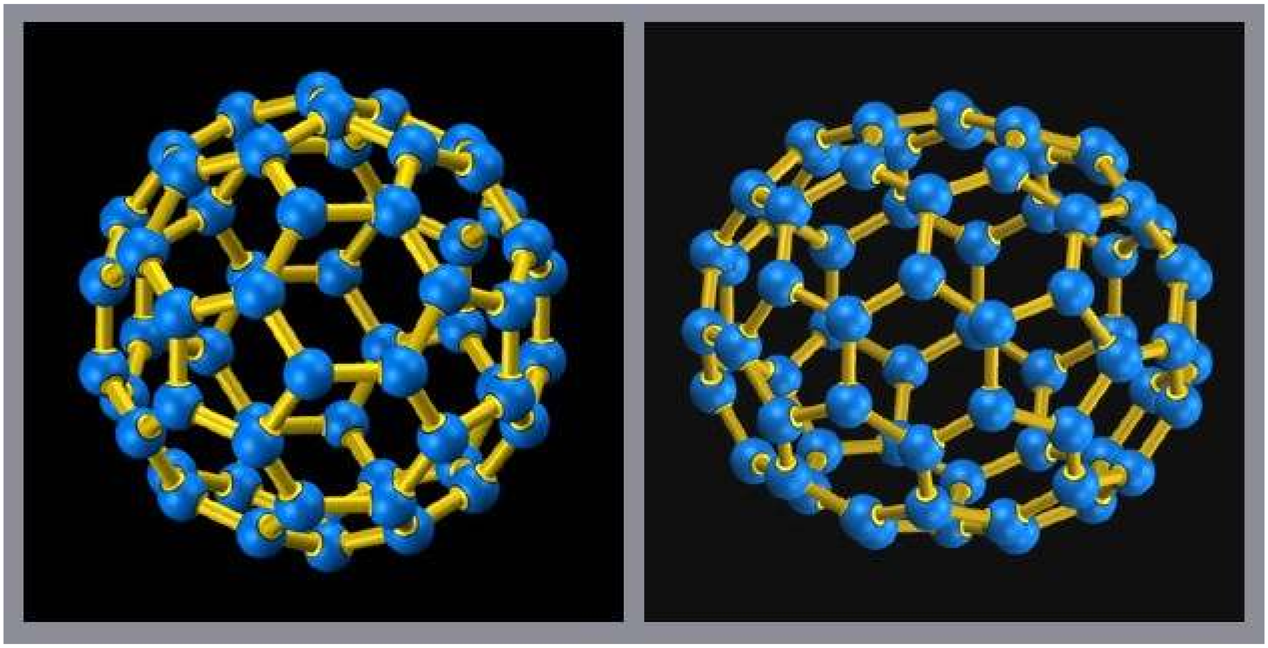
Crystals of rocky minerals formed when *magma* (molten rock) cooled slowly on the earth's surface, or when minerals got deposited from saturated solutions. A wide variety of shapes and sizes are observed in rock crystals. Common shapes are: Cube, tetrahedron, octahedron, dodecahedron, twin tetrahedral pyramid, square and hexagonal prisms terminated by corresponding pyramids etc. Some of these rock crystals are huge in size, with the largest being a beryl crystal 18 metres long discovered in Madagascar.

Carbon structures:

The element *Carbon* has the unique property of taking up different forms, or allotropes, such as diamond and graphite. *Diamond* is the hardest naturally occurring substance. In diamond, each carbon atom is surrounded by 4 carbon atoms occupying the vertices of a tetrahedron. The carbon atoms form a three-dimensional *tetrahedral lattice*, in which billions of atoms are bonded together to form a giant molecule encompassing the whole material. Since every piece of diamond is a fragment of a single molecule, diamond possesses great strength.

Fullerenes:

Carbon also occurs as a third allotrope in which the carbon atoms form large cage-like molecules. This allotrope is called *Buckminsterfullerene* or simply *Fullerene*, in honour of the architect Buckminster Fuller who conceived the geodesic dome. It is amazing that a structural form that was conceived in the mind of a great architect has subsequently been found to be the molecular structure of a remarkable group of materials! The most common fullerene of carbon is C_{60} in which the carbon atoms occupy the 60 nodes of the Buckyball or Truncated icosahedron. Other *Spheroidal* fullerenes also exist, such as C_{70}, C_{84} etc. See Figures.



C60 and C70 Fullerenes

Fullerene was discovered unexpectedly by Richard Smalley, Robert Curl and Harry Kroto in 1985, while investigating the manner in which carbon atoms clustered in the atmosphere of a red giant star as it cooled. In the experiment, a laser beam vapourized carbon into a helium carrier gas. Hydrogen and nitrogen gases were added and the hot mixture allowed to expand rapidly and cool adiabatically. Apart from the expected hydrocarbons, carbon fullerenes were detected in the cooled mixture by mass spectrometry. The 1996 Nobel prize in Chemistry was awarded to the three co-discoverers of fullerene.

Carbon fullerenes exhibit unique properties. The fullerene molecule is very stable. C_{60} is a brownish yellow powder. At room temperatures, the molecules of C_{60} spin freely. On heating, C_{60} sublimates to the vapour form.

Following the discovery of the fullerene, there were wild speculations about its potential applications as a super-lubricant, superconductor etc. The initial euphoria has now died down. However, several promising lines of research are being pursued.

Vapour-deposition of C_{60} leads to a smoother diamond coating on materials than vapour-deposition of graphite.

When exposed to ultraviolet light, C_{60} buckyballs polymerize, forming bonds between adjacent molecules. Normal C_{60} dissolves in toluene, but polymerized C_{60} does not. Because of this property, C_{60} has been used as a photosensitive etching medium.

Trapping other elements inside the buckyball cage produces *Endohedral fullerenes* possessing interesting properties. One such compound is K_3C_{60}, which is a superconductor with a critical temperature T_c of 19K. Other alloyed fullerenes have been found with T_c upto 40K.

Trapping molecules of a drug inside the buckyball cage might one day permit targeted drug delivery to specific organs of the body. Since there is not enough space inside the buckyball for too many atoms, the elongated spheroidal fullerenes such as C_{84} are being studied for this application.

Carbon nanotubes, an offshoot of fullerene research, are cylindrical carbon structures, each a few nanometers in diameter and upto about 1 mm long. Nanowires, made of carbon nanotubes having a chain of metal atoms trapped inside, have unique properties and hold promise in diverse fileds such as superconductivity and nano-transistors.

The day is not far off when fullerenes and nanotubes would find extensive use in diverse practical applications.

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