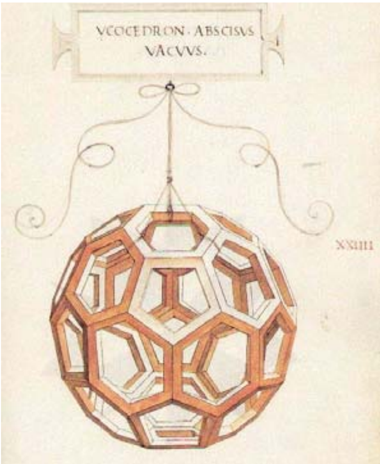
E. A. Katz. Fullerenes, Carbon Nanotubes and Nanoclusters: Genealogy of Forms and Ideas [in Russian]. Editorial URSS, LKI, Moscow, 2008

Fullerene-like structures: from mathematics to chemistry, physics, biology and architecture

Eugene A. Katz

Dept. of Solar Energy and Environmental Physics,
The Jacob Blaustein Institutes for Desert Research,
Ben-Gurion University of the Negev,
Sede Boqer Campus



Leonardo, 1509

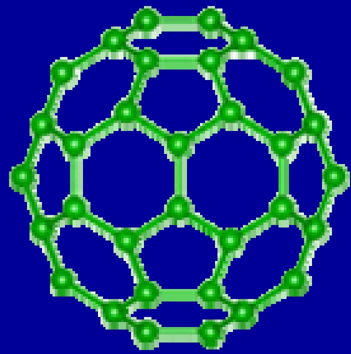
A. Dürer, 1497-98

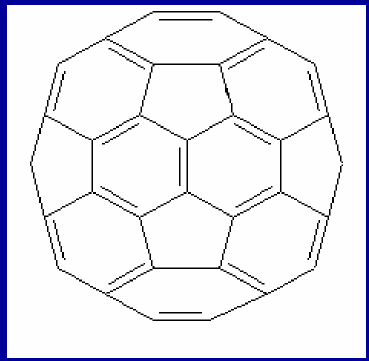
Contents

Allotropes of carbon

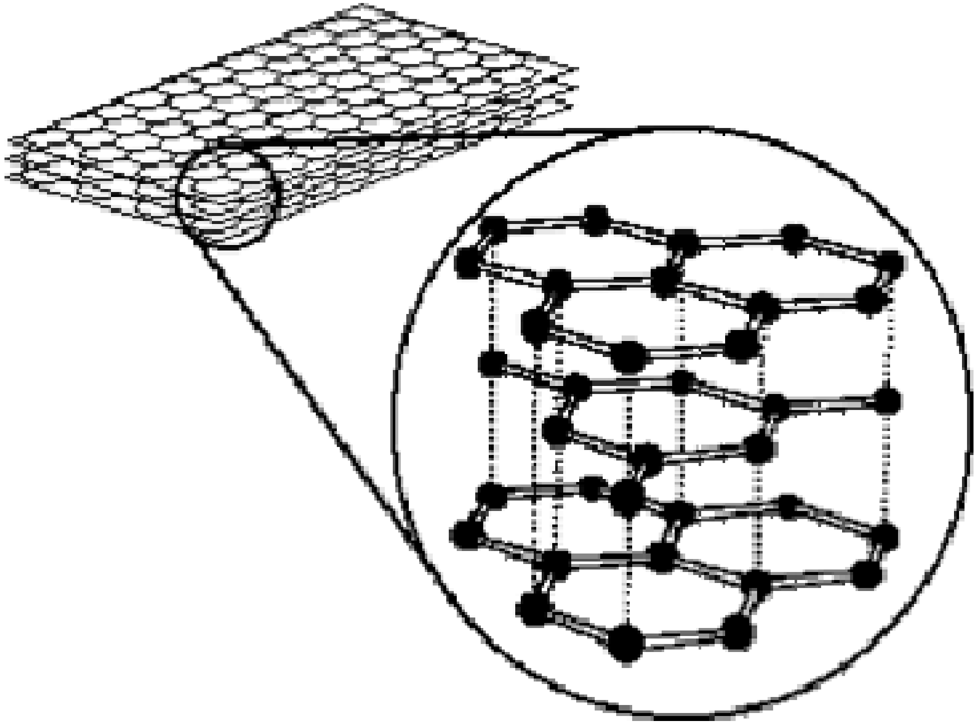
Graphite and diamond

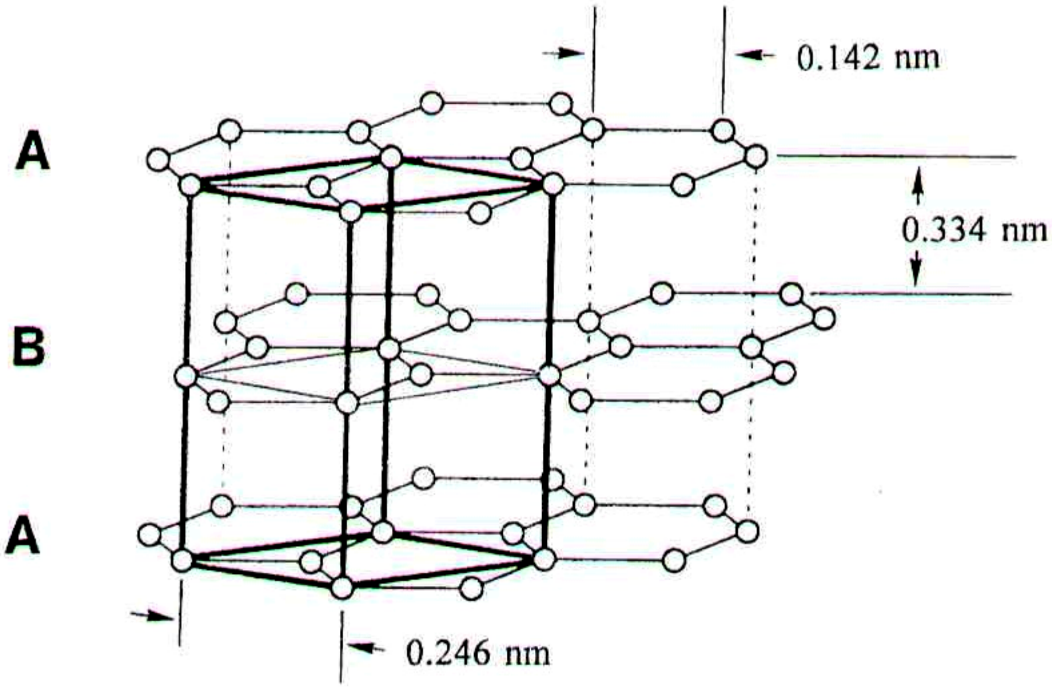
C_{60}





1985



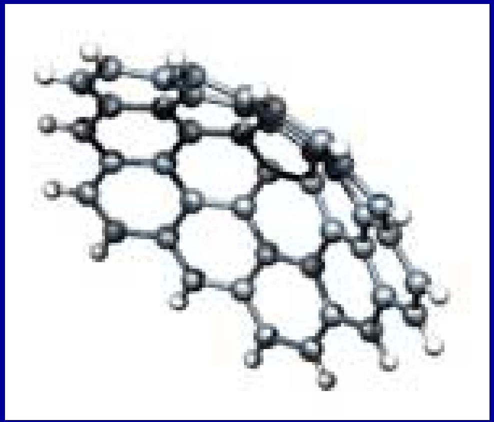


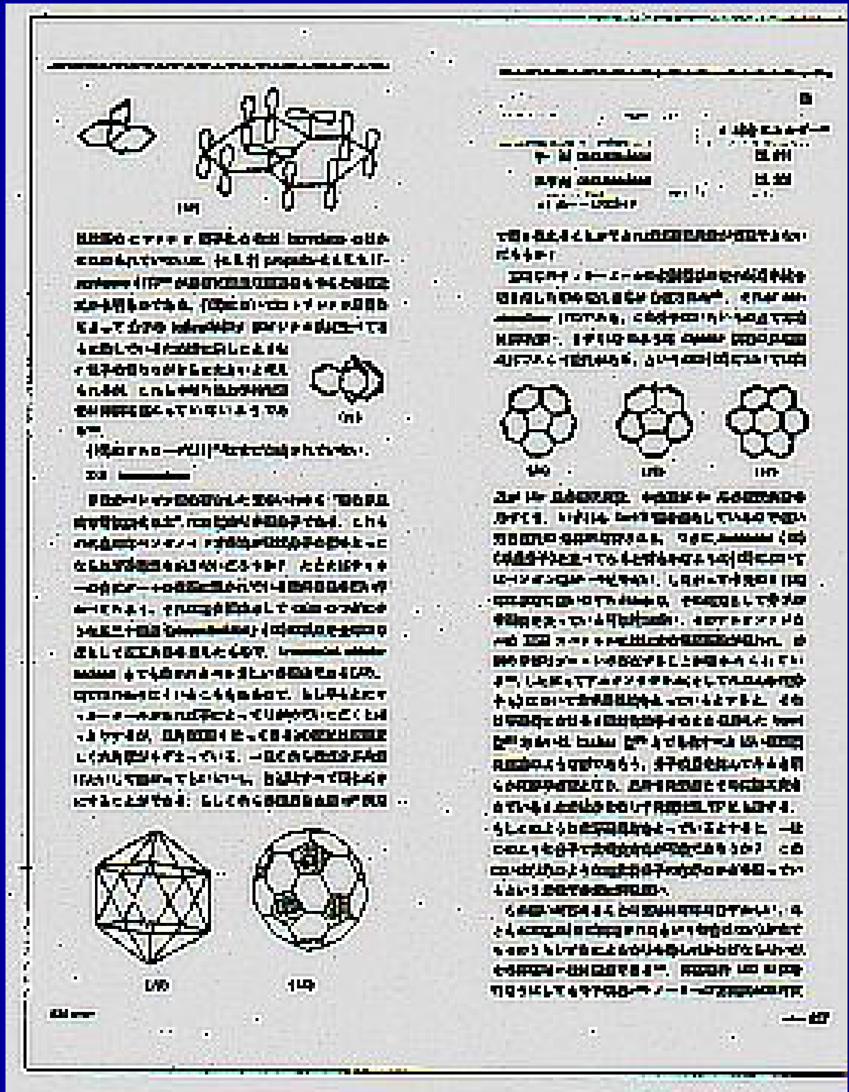
Crystalline structure of graphite

D.E.H. Jones, *New Scientist* 32, 245 (3 November 1966).

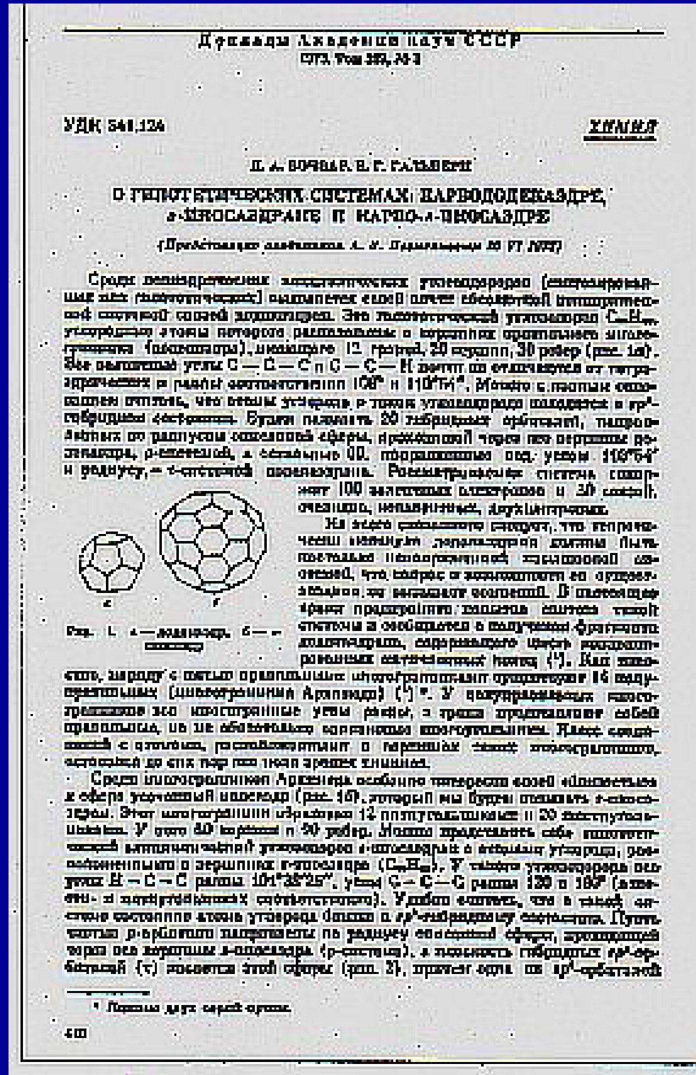
D. E. H. Jones, The Inventions of Daedalus (W. H. Freeman, Oxford, 1982).

Implanting of pentagonal defects into a hexagonal graphene layer might transform this flat layer into a giant closed-cage molecule of carbon





E. Osawa. *Kagaku (Kyoto)*, 25 (1970) 854 [in Japanese].



Доклады Академии наук СССР

1973. Том 209, № 3

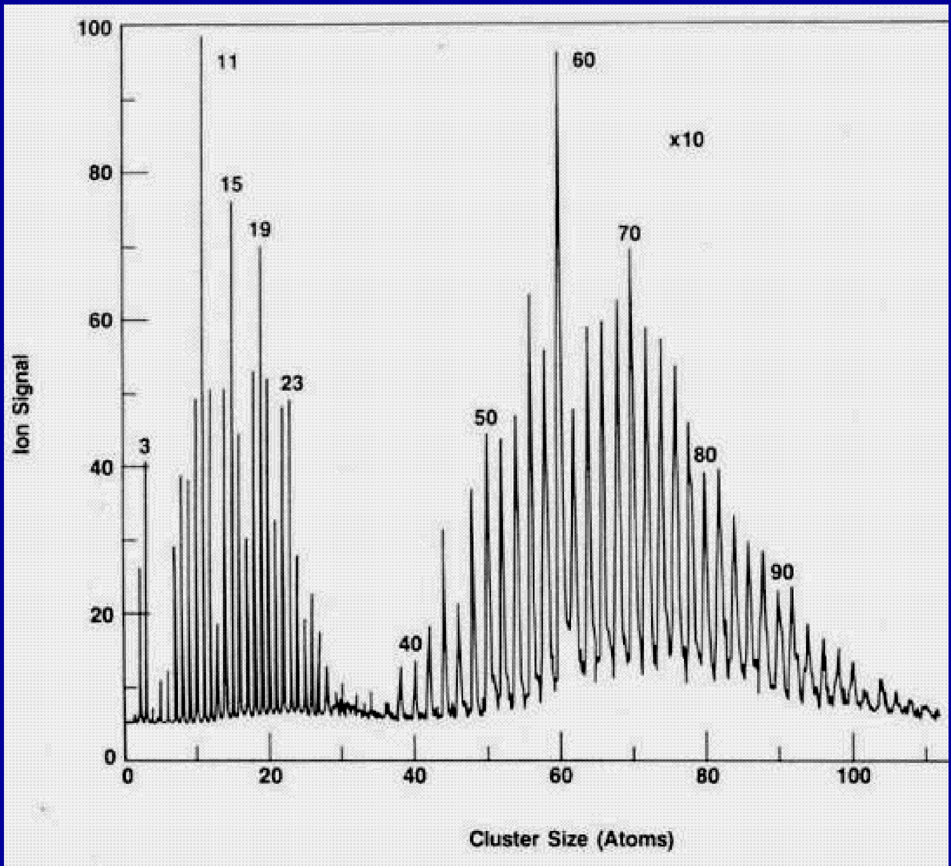
УДК 541.124

ХИМИЯ

Д. А. БОЧВАР, Е. Г. ГАЛЬПЕРН

О ГИПОТЕТИЧЕСКИХ СИСТЕМАХ: КАРБОДОДЕКАЭДРЕ, s-ИКОСАЭДРАНЕ И КАРБО-s-ИКОСАЭДРЕ

D.A. Bochvar and E.G. Gal’pern. *Dokl. Akad. Nauk SSSR*, 209, 610 (1973) [in Russian].



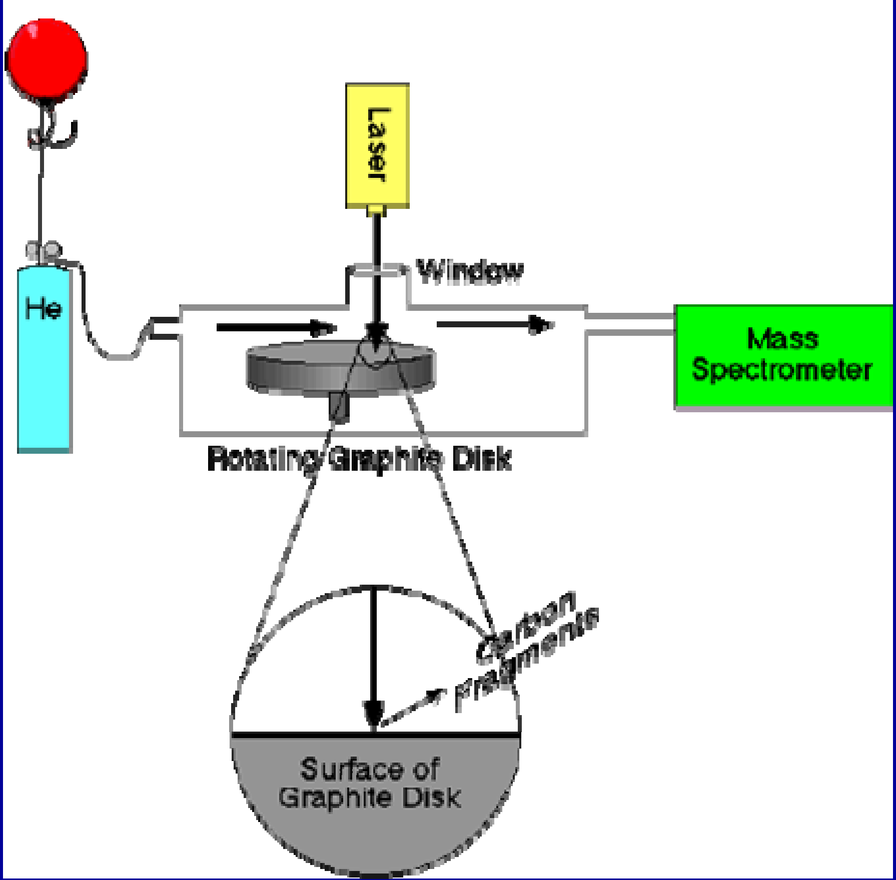
E.A. Rohlfing, D.M. Cox, A. Kaldor, J. Chem. Phys. 81, 3322 (1984).

Three distinct regions:

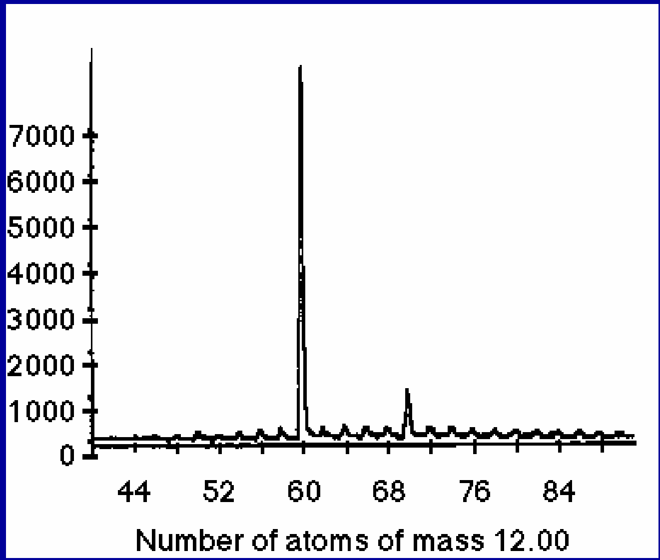
(1) n<25 - small clusters, consisting of the chains and monocyclic rings (well known from the earlier studies);

(2) 25 < n< 35 -"forbidden zone";

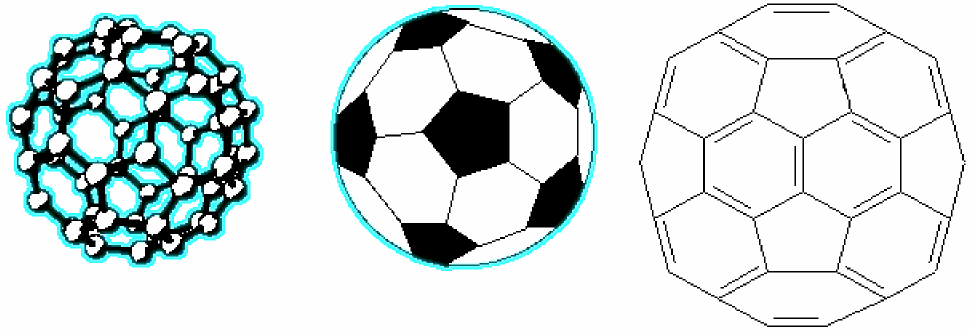
(3) 36 < n < 150 – even-numbered clusters (fullerenes)



September 1985, Rice University



Structure of C_{60}



Truncated icosahedron

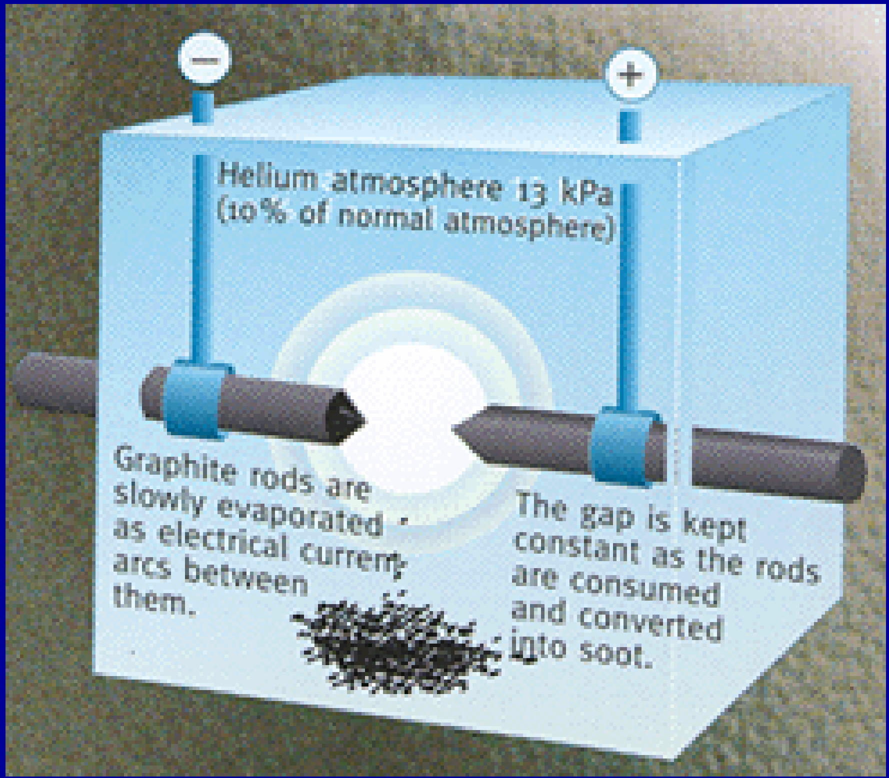
12 pentagons;

20 hexagons

C_{60}-Buckminsterfullerene

H.W. Kroto, J.R. Health, S.C. O'Brien, R.F. Curl and R.E. Smally, *Nature* 318, 162 (1985).

W. Kr ätschmer, L.D. Lamb, K. Fostiropoulos and D.R. Huffman, *Nature*, 347, 354 (1990).



Arc vaporization apparatus for generation fullerene containing soot

fullerene soot

↓

toluene extraction

↓

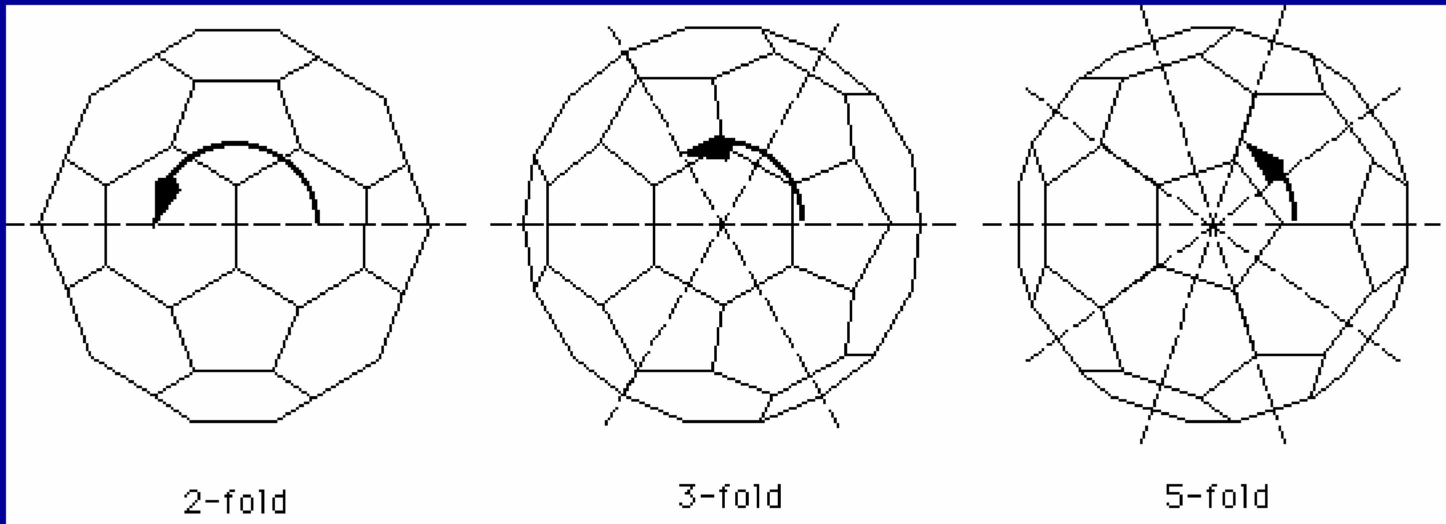
chromotographic separation

↓

C_{60} (80-90 %)	C_{70} (10-15 %)	higher fullerenes (<1%)

"The story of C_{60} cannot be recounted without reference to its beauty which results from the incredible symmetry. Another important aspect of the molecule's aura lies in the name *buckminsterfullerene* and the direct association with the geodesic domes designed by Buckminster Fuller. It invests this elegant molecule with a charisma that has fascinated scientists, delighted lay people and has infected children with a new enthusiasm for science."

H.W. Kroto, Nobel Lecture, December 7, 1996



15 rotation axes (180°)   10 rotation axes (120°)   6 rotation axes (72°)

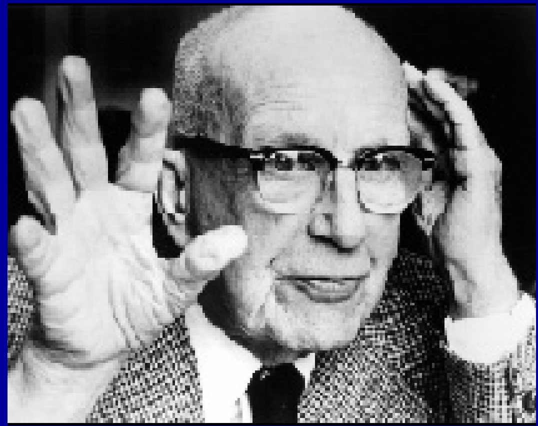
"These groups (I, I_h) are of no physical interest since they have not realized themselves as symmetry groups of molecules"

L. Landau and E. Lifshits, Quantum Mechanics, 1948.

2. Buckminster Fuller's energetic geometry and geodesic domes

<u>Richard Buckminster Fuller</u> (1895-1983) –

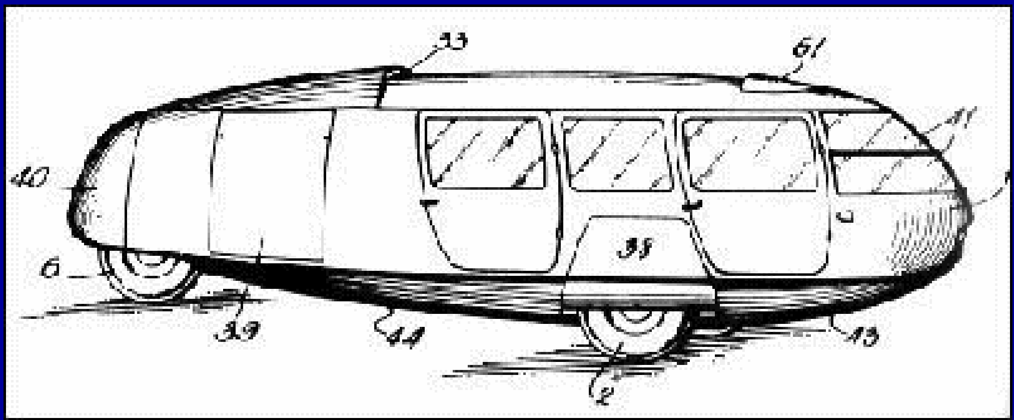
architect, philosopher, engineer, inventor, author, cartographer, geometrician, futurist, teacher and poet… one of the most original thinkers of the second half of XX century (*Encyclopedia Britanica*)

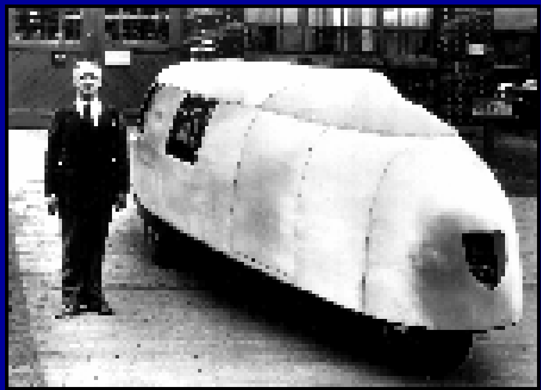


1927, the aim: a non-profit search for design patterns that could maximize the social uses of the world energy and industrial resources

Dymaxion House, 1928.Wichita, Texas

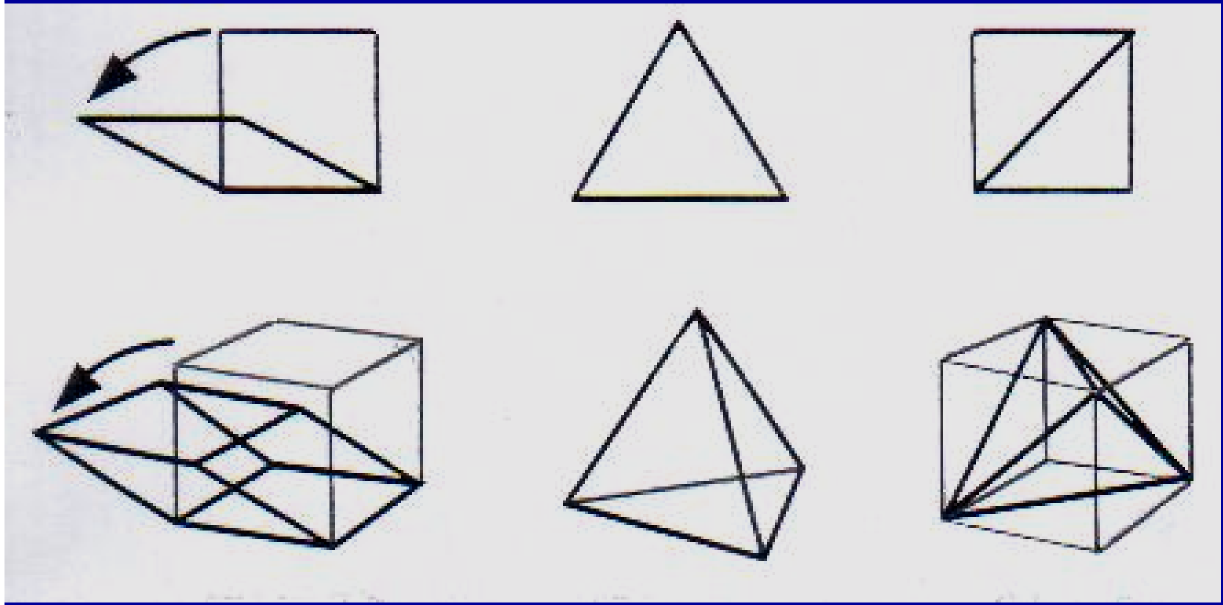
Dymaxion Car, 1928-1933





190 km/hour, 12 passengers

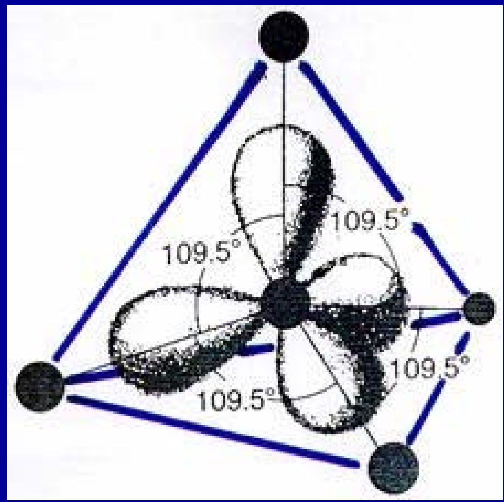
Energetic-Synergetic Geometry



Tetrahedral configuration of carbon bonds

Jacobus H. van't Hoff, 1874

First Nobel Price in Chemistry, 1901



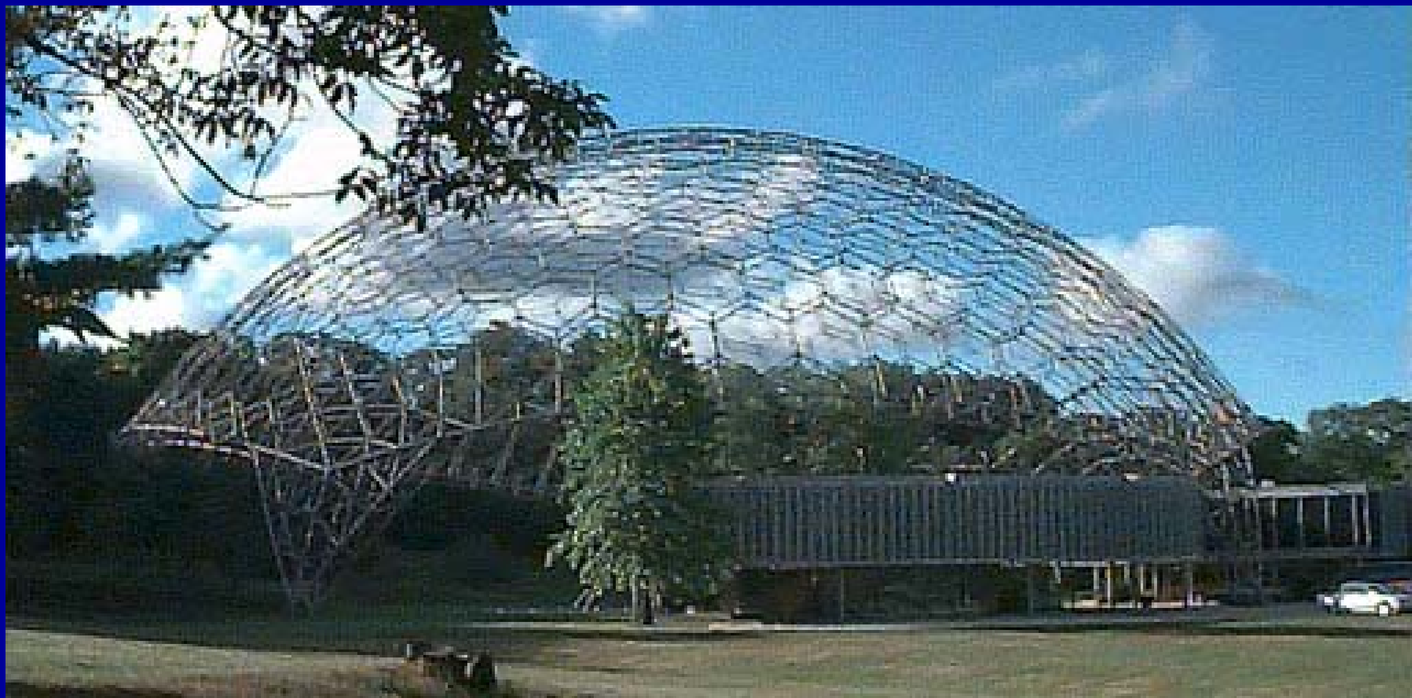
A	B	C
Unstable shapes Square and Cube	**Stable shapes Triangle and Tetrahedron**	**Stable shapes support the unstable ones**

Square and cube (A) have no inherent structural strength – they can collapse in any direction. The triangle and tetrahedron (B) have built-in strength and stability. Column (C) shows how square and cubes become stable *only* when turned into triangles and tetrahedra.

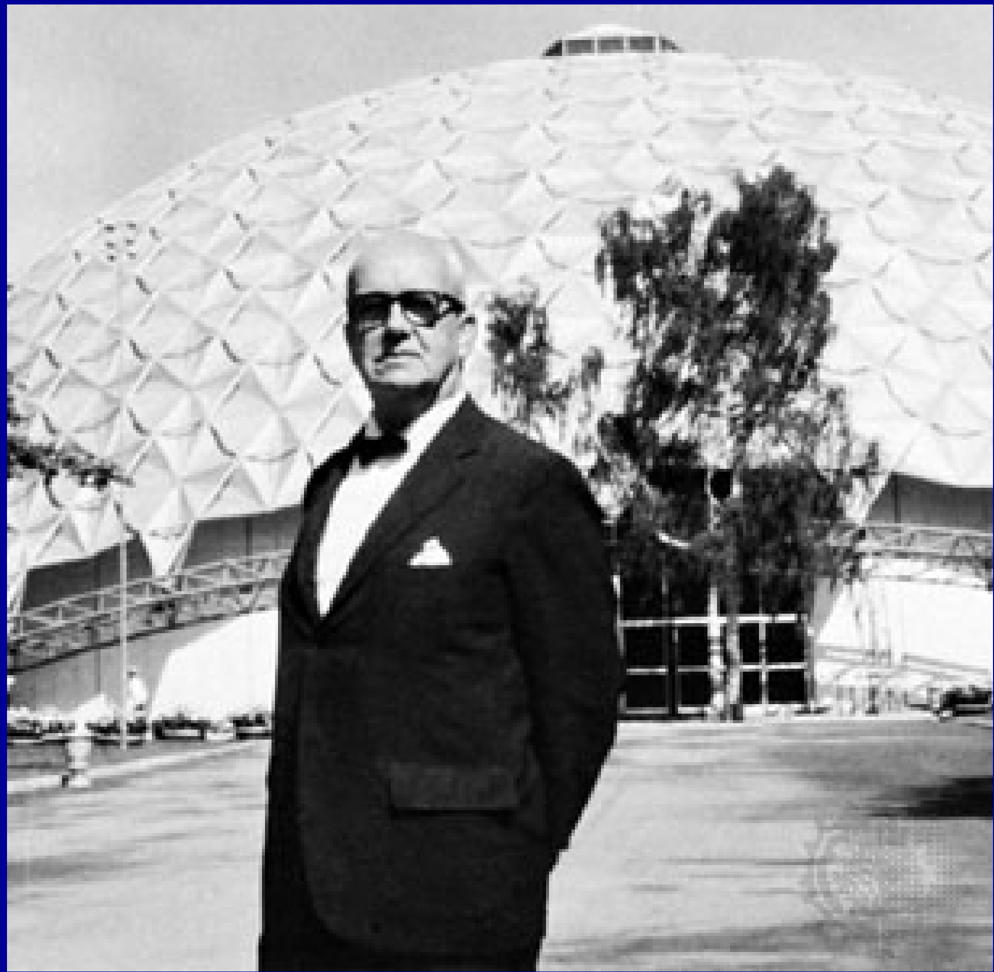
1954 - the first Bucky's patent on geodesic domes;

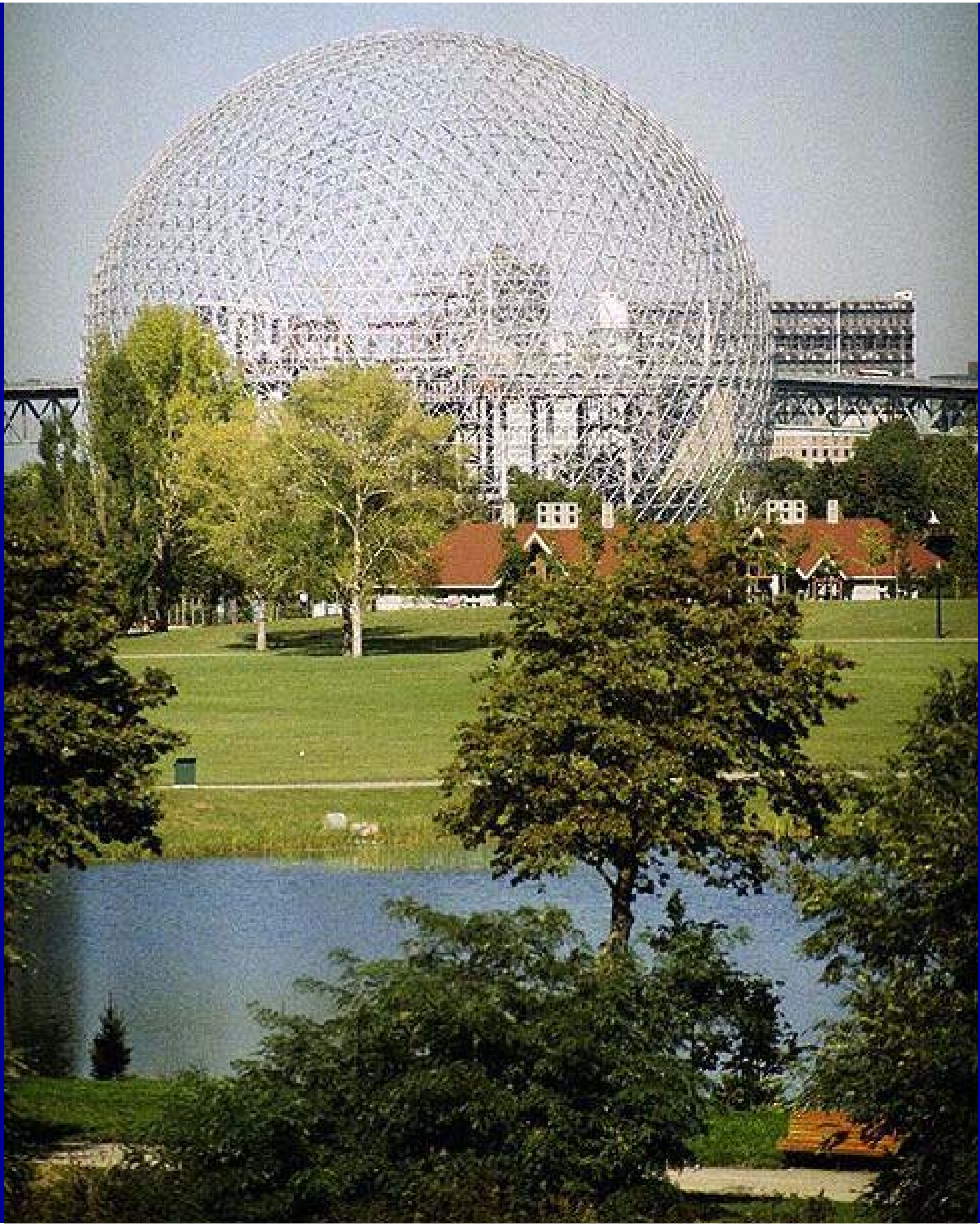
1958 - geodesic dome for the Union Tank Car Company (Los Angeles), 117 m diameter and 35 m height;

1958-1959 - Headquarter of the "ASM International", the Materials Information Society (Cleveland, Ohio)



1959 – Pavilion of the first US exhibition in Moscow





1967 –
the US Pavilion at
***Expo'67*, Montreal, Canada**

Geodesic domes (definitions & statements)

Geodesic sphere **is a polyhedral structure could be effectively inscribed in a sphere.**

Geodesic domes **are fractional parts of complete *geodesic spheres*. Actual structures range from less than 5% to 100% (a full sphere).**

Spaseship Earth Pavilion at Disney's Epcot

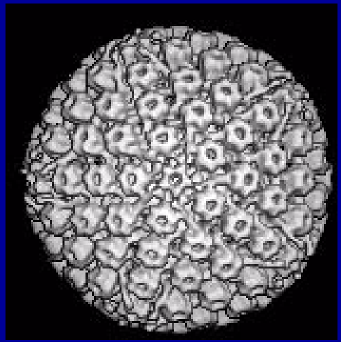
A *sphere* is already efficient: it encloses *the most volume with the least surface*. Thus, any dome that is a portion of a sphere has the least surface through which to lose heat or intercept potentially damaging winds.

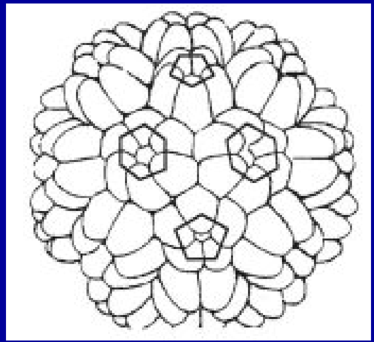
A geodesic dome uses a pattern of self-bracing *triangles* that gives maximum strength and stability using the least material possible.

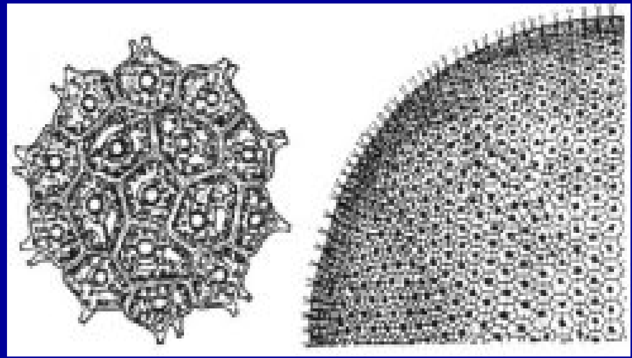
***Frequency* of a dome relates to the number of smaller triangles into which it is subdivided. A high frequency dome has more triangular components and is more smoothly curved and sphere-like**

Geodesic domes get stronger, lighter and cheaper per unit of volume as their frequency and size increase - just the opposite of conventional building

Fullerene-like viruses
(small geodesic domes with icosahedral symmetry)

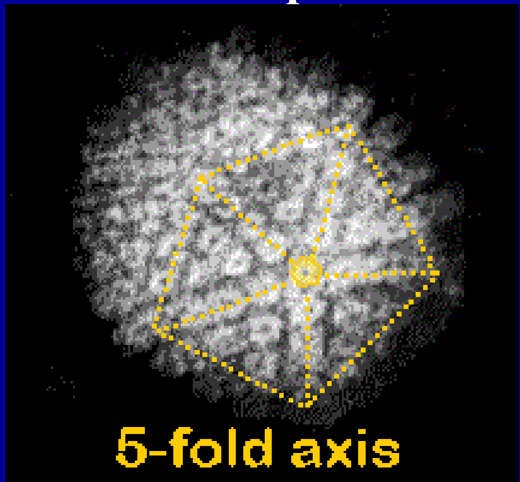






20-300 nm

Herpes



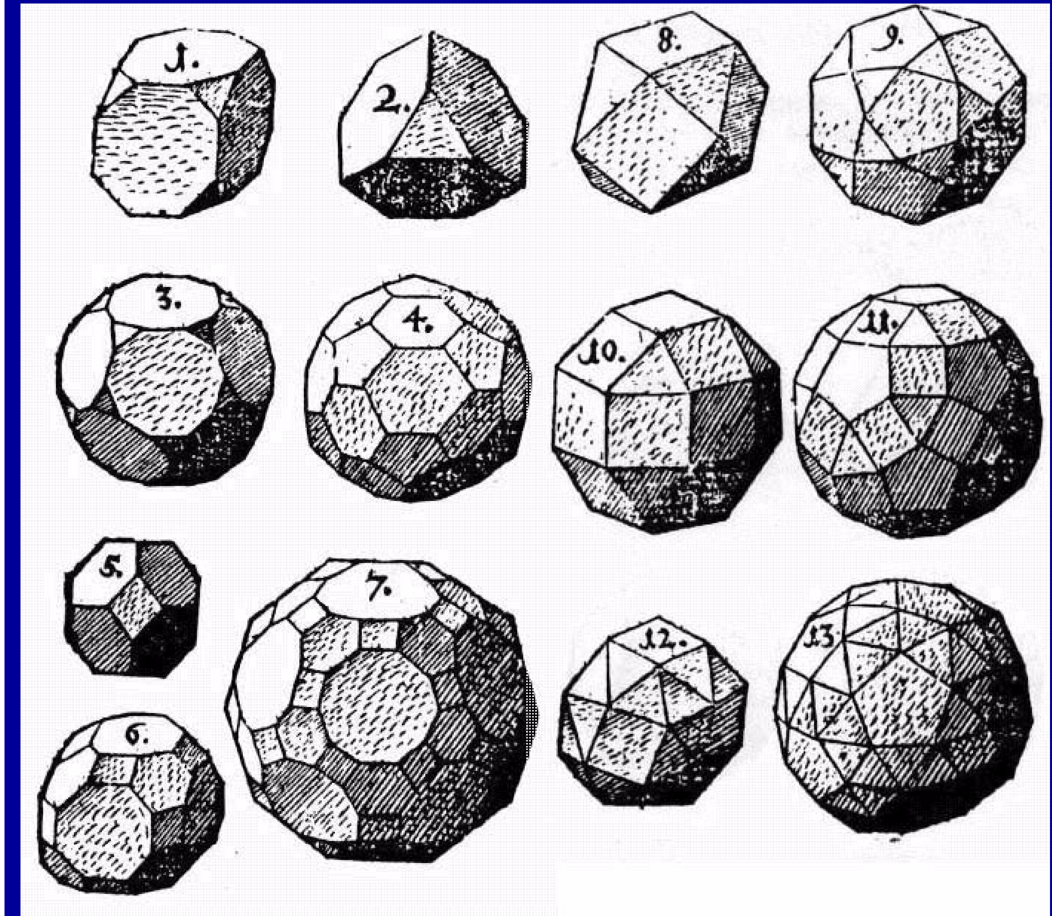
D.L.D. Caspar and A. Klug. Physical Principles in the Construction of Regular Viruses, in Cold Spring Harbor Symp. Quant. Biol. V.27, 1 (1962):

"The solution we have found was, in fact, inspired by the geometrical principles applied by Buckminster Fuller in the construction of geodesic domes and his physically oriented geometry of efficient design."

Aaron Klug– Nobel Price in chemistry, 1982

3. Long history of exploration of polyhedra: science and fine art

Archimedes (287-212 b.c.): first researcher of truncated icosahedron



From Johannes Kepler's "Harmonice Mundi" ("The Harmony of the World"), 1619

***Archimedian polyhedra* or *archimedean solids*: polyhedra with faces as regular polygons and vertices located in equivalent positions (as carbon atoms in the C_{60} molecule).**

Archimedean solids consist of at least 2 different types of polygons (that makes them different from *regular* *<u>polyhedra</u>* or *platonic solids*)

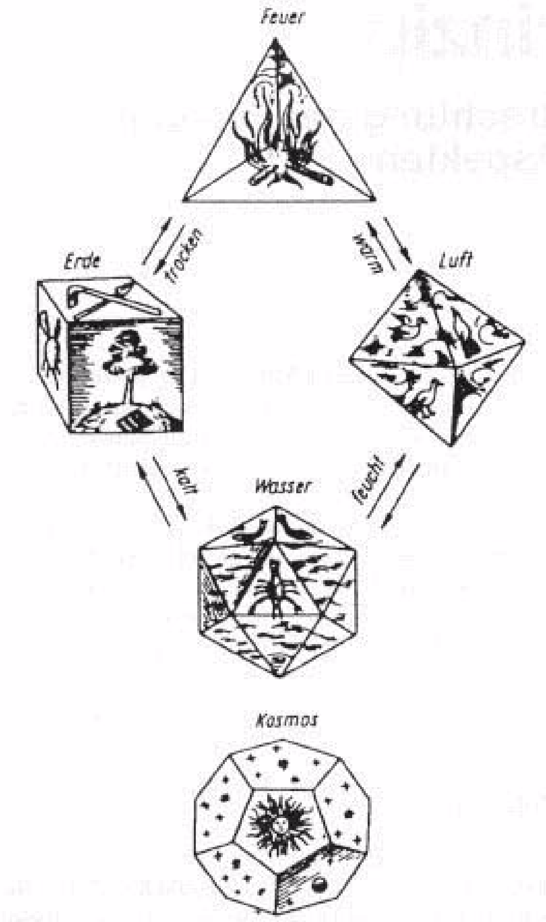
Platonic solids (regular polyhedra)

Classical elements:

Plato (~420 – 347 b.c.), probably, Pithagoreans

- Tetrahedron - fire,
- Cube - earth,
- Octahedron - air,
- Icosahedron - water,

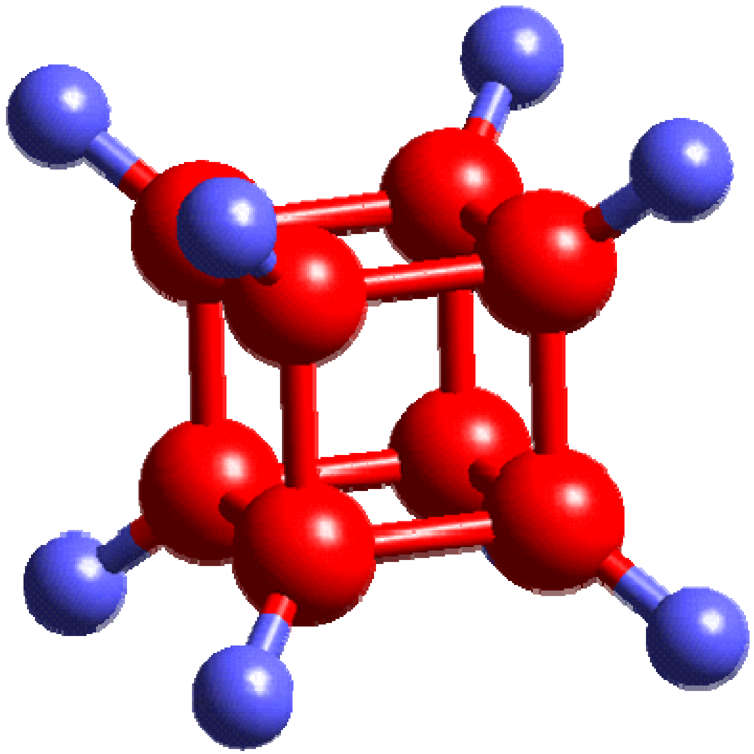
Hipparchus (? – 127 b.c.) Dodecahedron - the universe



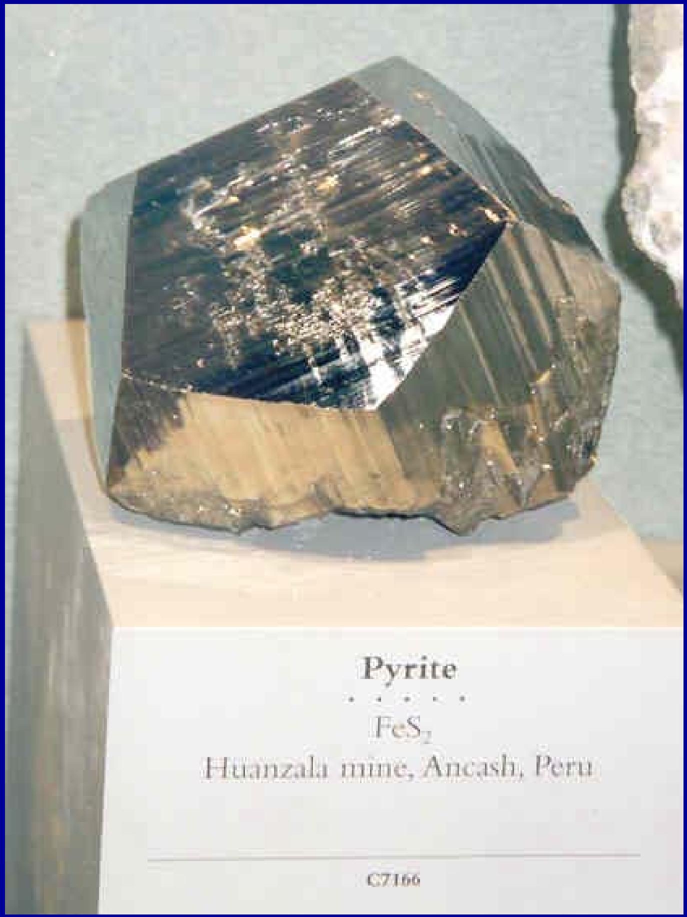
From Johannes Kepler's "Harmonice Mundi" ("The Harmony of the World"), 1619

“Forbidden” chemical compound –

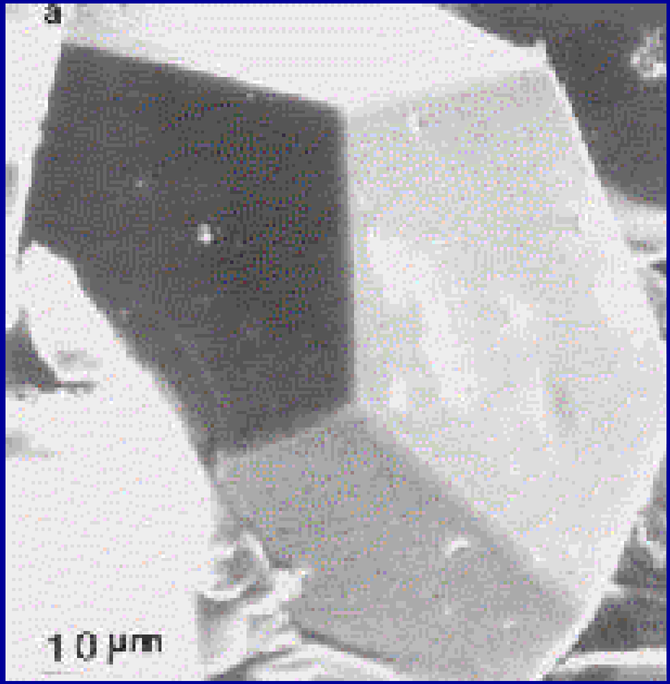
Cubane – C_8H_8 (1964)



Dodecahedron



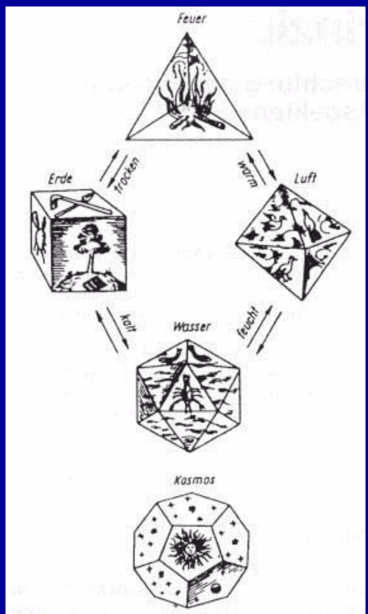
Natural History Museum,
Washington, D. C.

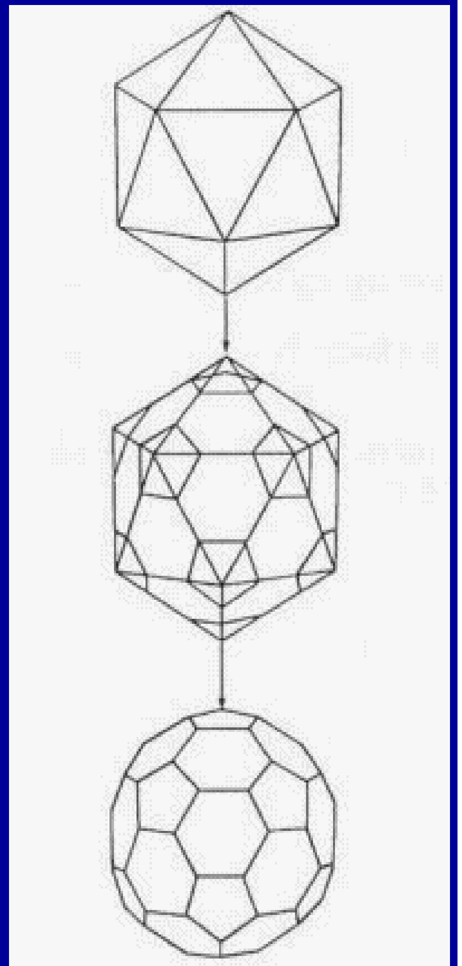


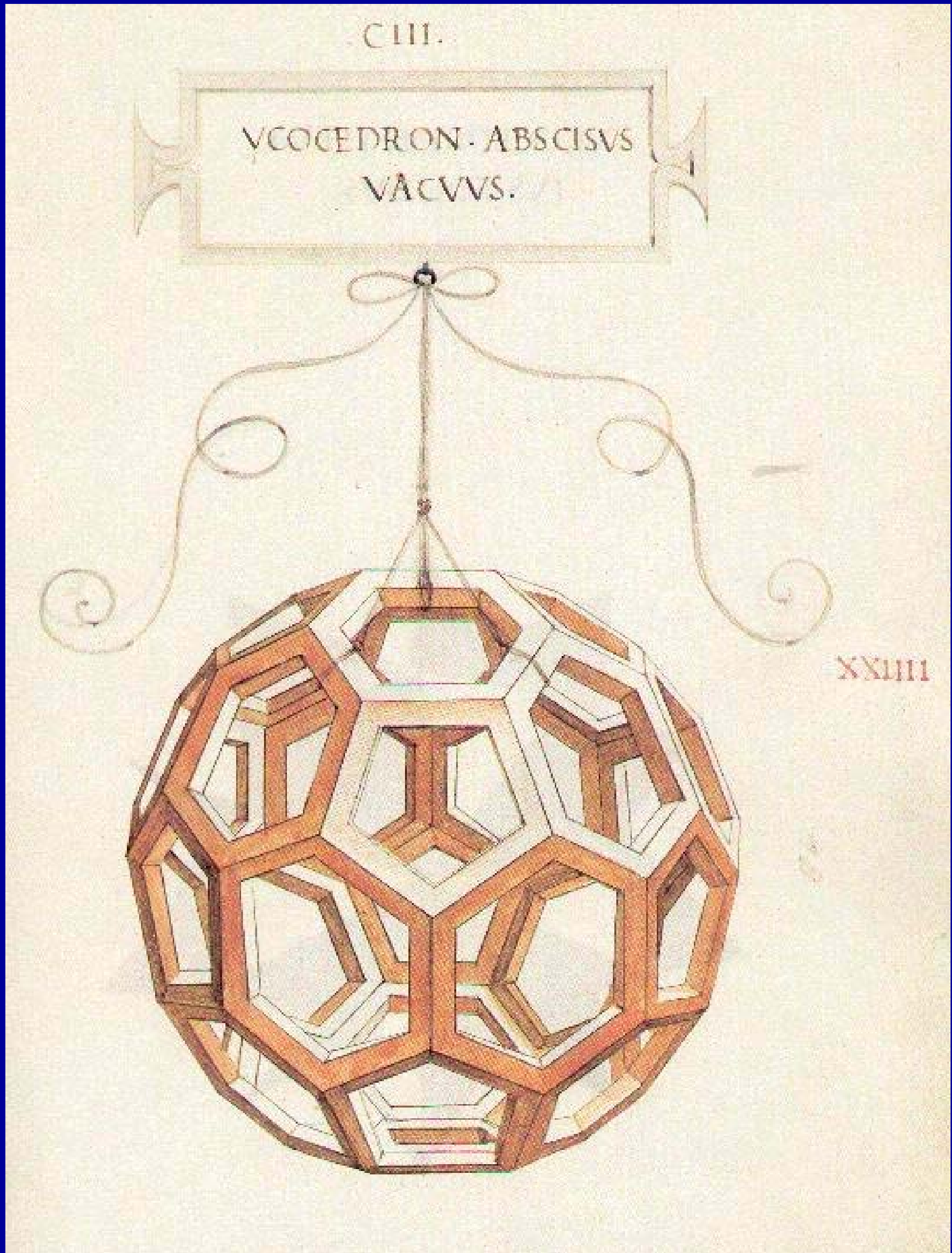
Al-CU-Fe quasicrystal

Characteristics of platonic solids

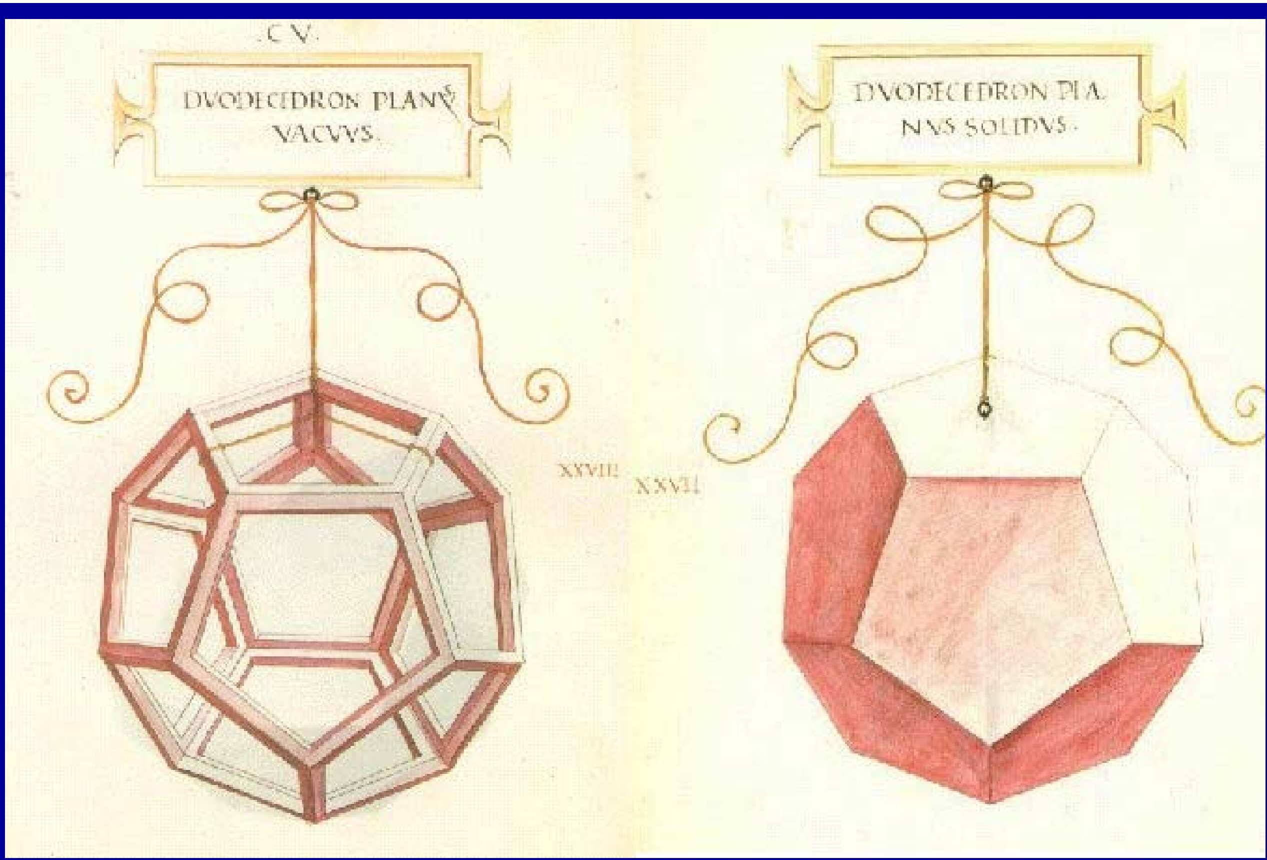
Polyhedron	Edges in each face, *m*	Edges that connect in each vertice, *n*	Faces, F	Edges, E	Vertices, V	F-E+V
Tetrahedron	3	3	4	6	4	2
Cube	4	3	6	12	8	2
Octahedron	3	4	8	12	6	2
Icosahedron	3	5	20	30	12	2
Dodecahedron	5	3	12	30	20	2



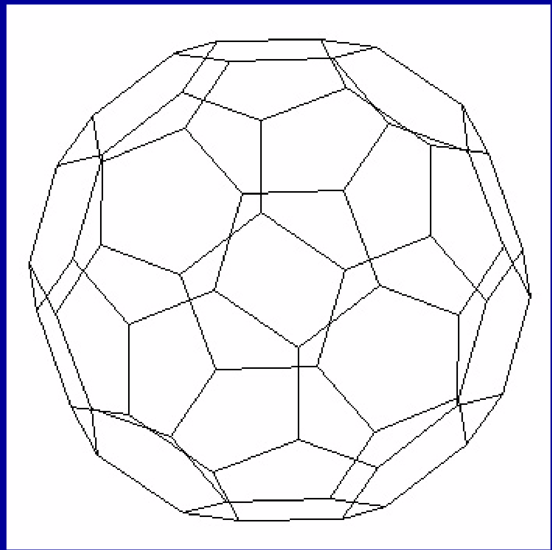




Leonardo's drawing of truncated icosahedron from Luka Pacioli's book "The Devine Proportion" ("De Devina Proportione"), 1509



Leonardo's drawing of dodecahedron by a method of *solid segments* and *solid faces* from Luka Pacioli's book "The Devine Proportion" ("De Devina Proportione"), 1509



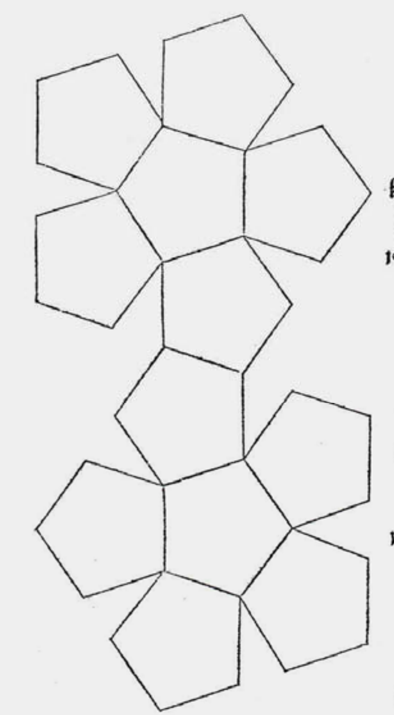
Luka Pacioli, 1445-1517

Rombicuboctahedron

Jacopo de Barbari. Luka Paciolli’s portrait, 1495

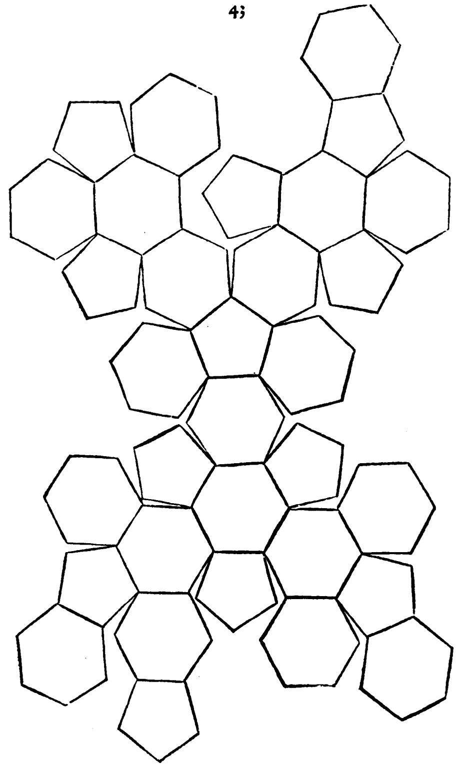
Albrecht Durer, 1471-1528

Self-portrait, 1498



33

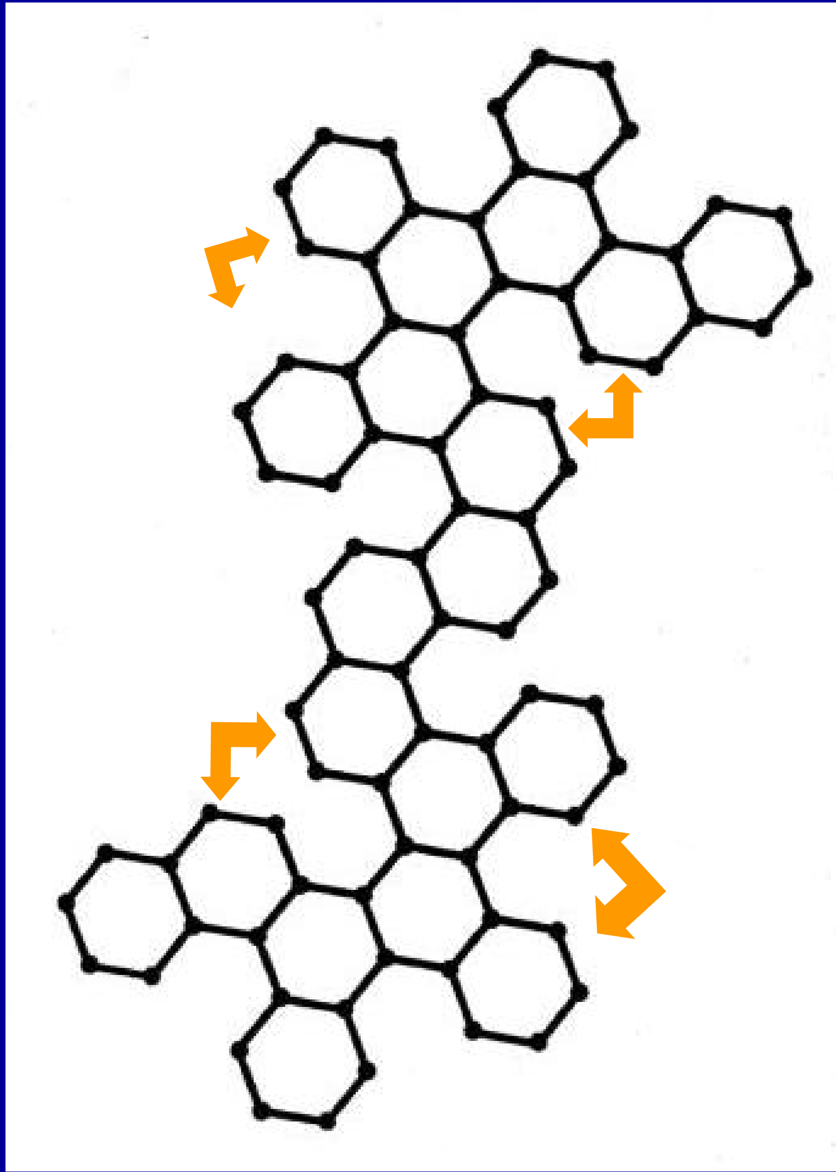
Die ſpera oder ein kugel wen man ſie durch jr mittag linien zerſchneydet / vnd in ein planum legt / ſo gewint ſie ein geſtal eins kams / wie jch das hie vnden kugels weyß / vnd offen hab aufgeriſſen.



Ein anders das mach auß zweintzig ſechſeckter flachen feldern / gleichſeitig vnd wincklich / ſo man darzu thut zwelf fünfeckter flacher felder / ſo die gleichſeittig gegen den ſechſeckten felden ſind / vnnd in jnen ſelbs auch gleich wincklich vnd ordenlich an eynander geſetzt werden / wie jch das offen im plano hernach hab aufgeriſſen / So man dann das alles zuſamen ſchleuſt / ſo würt ein corpus daraus / das gewinnet zwey vnd ſechtzig ecke / vnnd neüntzig ſcharpfer ſeitten / dis Corpus rüret in einer holen kugeln mit allen ſeinen ecken an.

43

Flat nets of dodecahedron and truncated icosahedron from Albrecht Durer's treatise "Painter's Manual" ("Underweysung der Messung"), *1525* .



F. Chung and S. Sternberg,
Mathematics and the Buckyball,

American Scientist 81, 56 (1993).

How to make a Buckyball

Please…

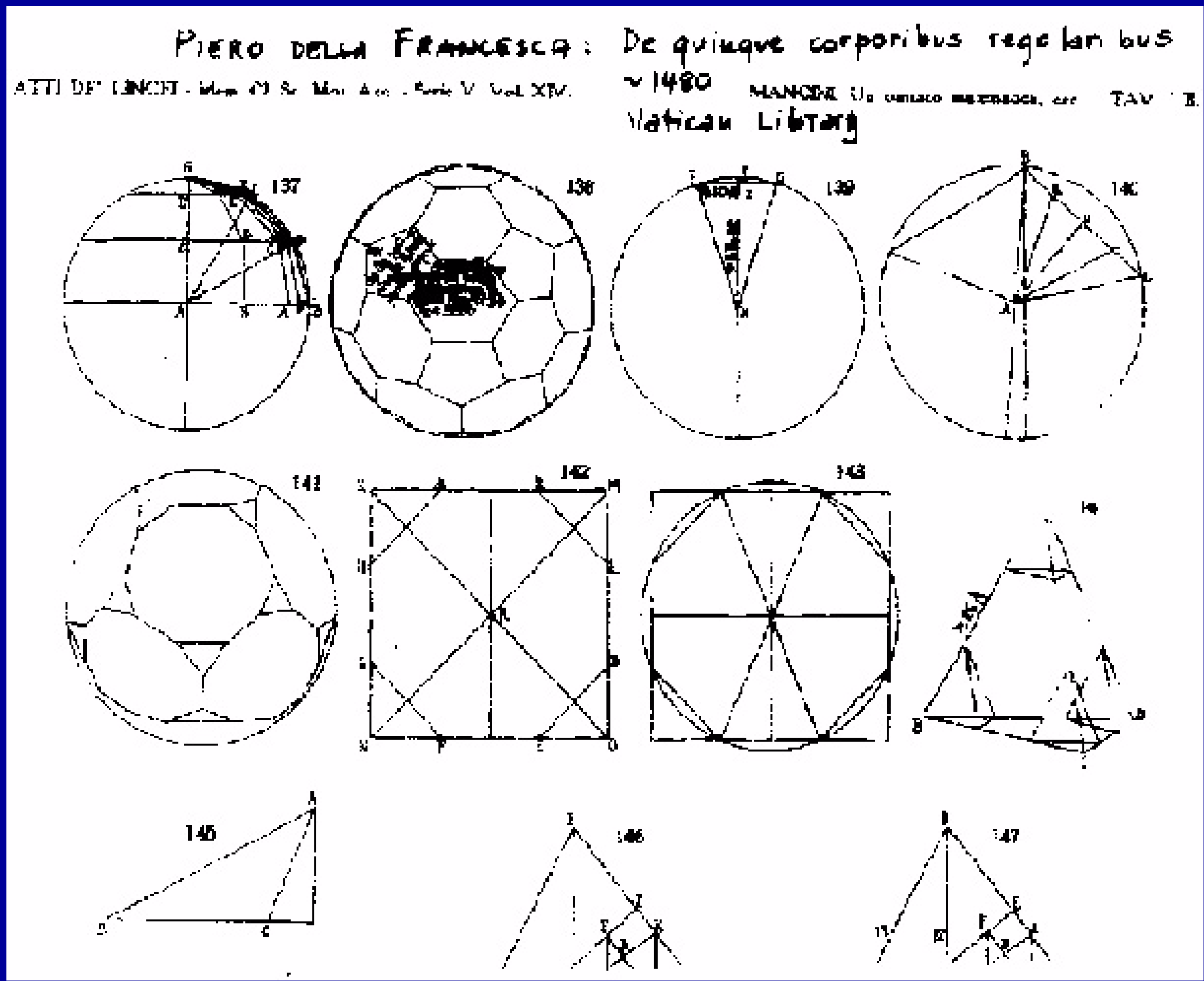
- Copy this net;

- Carefully cut it; -

-Start to curve it along the edges between the adjacent hexagons;

- Bring together each of the four pairs - of edges indicated by arrows and fasten them with small pieces of a transparent tape.

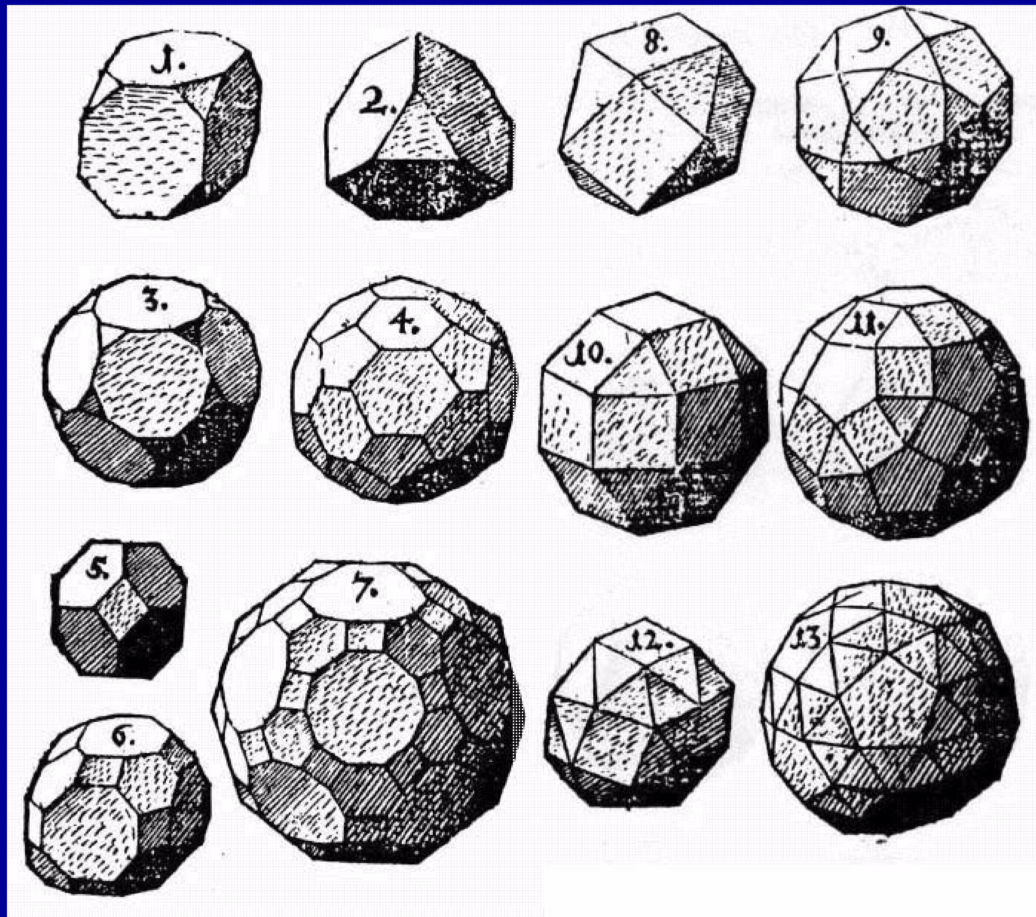
Piero della Franchesca (1420 - 1492)



The oldest known picture of truncated icosahedron from Pierro della Franchesca's manuscript "Short book on the five regular solids" ("Libbelus de quinque corporibus regularibus"), dated 1480, Vatican Library.

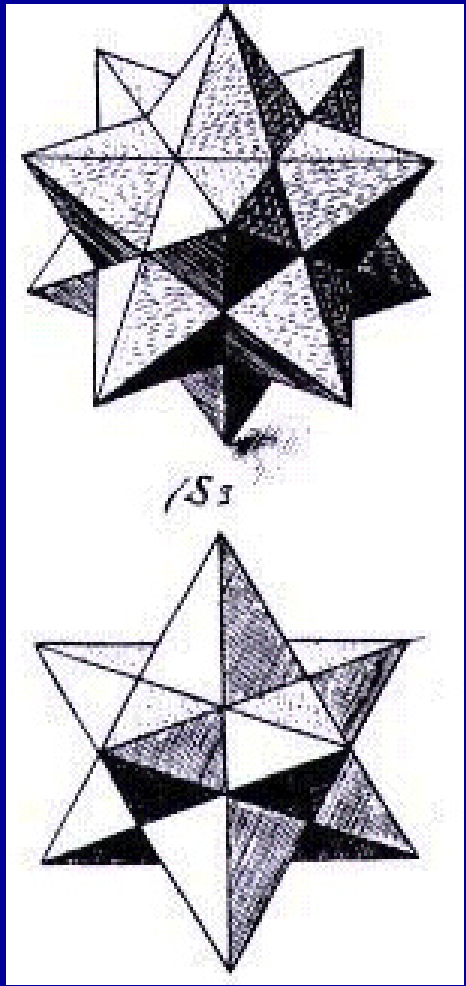
Mosaics (*intarsia*) created by Fra Govanni de Verona (1457 - 1525) for a church Santa Maria in Organo, Verona, about 1520.

Archimedian polyhedra or archimedean solids



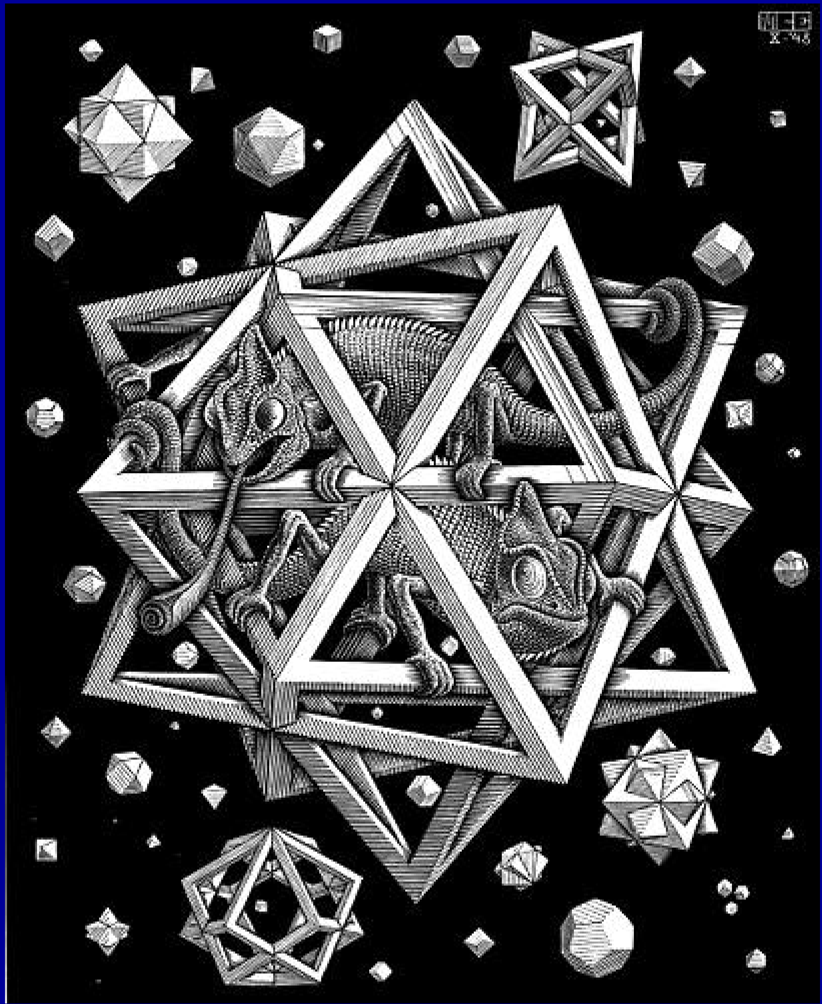
From Johannes Kepler's "Harmonice Mundi" ("The Harmony of the World"), 1619

Star-like regular polyhedra

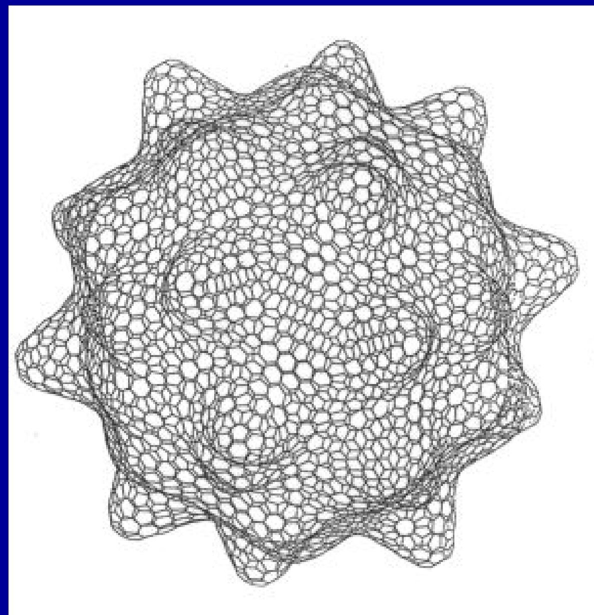


Johannes Kepler.
"Harmonice Mundi"
("The Harmony of the World"),

1619



M.C. Escher. Stars (1948)



Star-like carbon cluster

4. Leonhard Euler’s theorem

Leonhard Euler (1707 - 1783)

Euler’s theorem for convex polyhedra

$$F - E + V = 2$$

where F - faces, E - edges, V -vertices

Descartes (1596-1650)

L. Euler, Novi corumentarii
academie Petropolitanae 4, 109 (1752/3).

General Euler’s theorem

$$F - E + V = n$$

n – Euler’s parameter
(n = 0 for torus, n=2 - 2g for polyhedra with g ‘through holes’)

Euler's theorem for convex polyhedra

$$F - E + V = 2$$

where F - faces, E - edges, V -vertices

Fullerenes are closed-cage molecules of pure carbon in the shape of polyhedra with only pentagonal and hexagonal faces

$F = p + h$ where p and h are number of pentagonal and hexagonal faces, respectively

$2E = 5p + 6h$

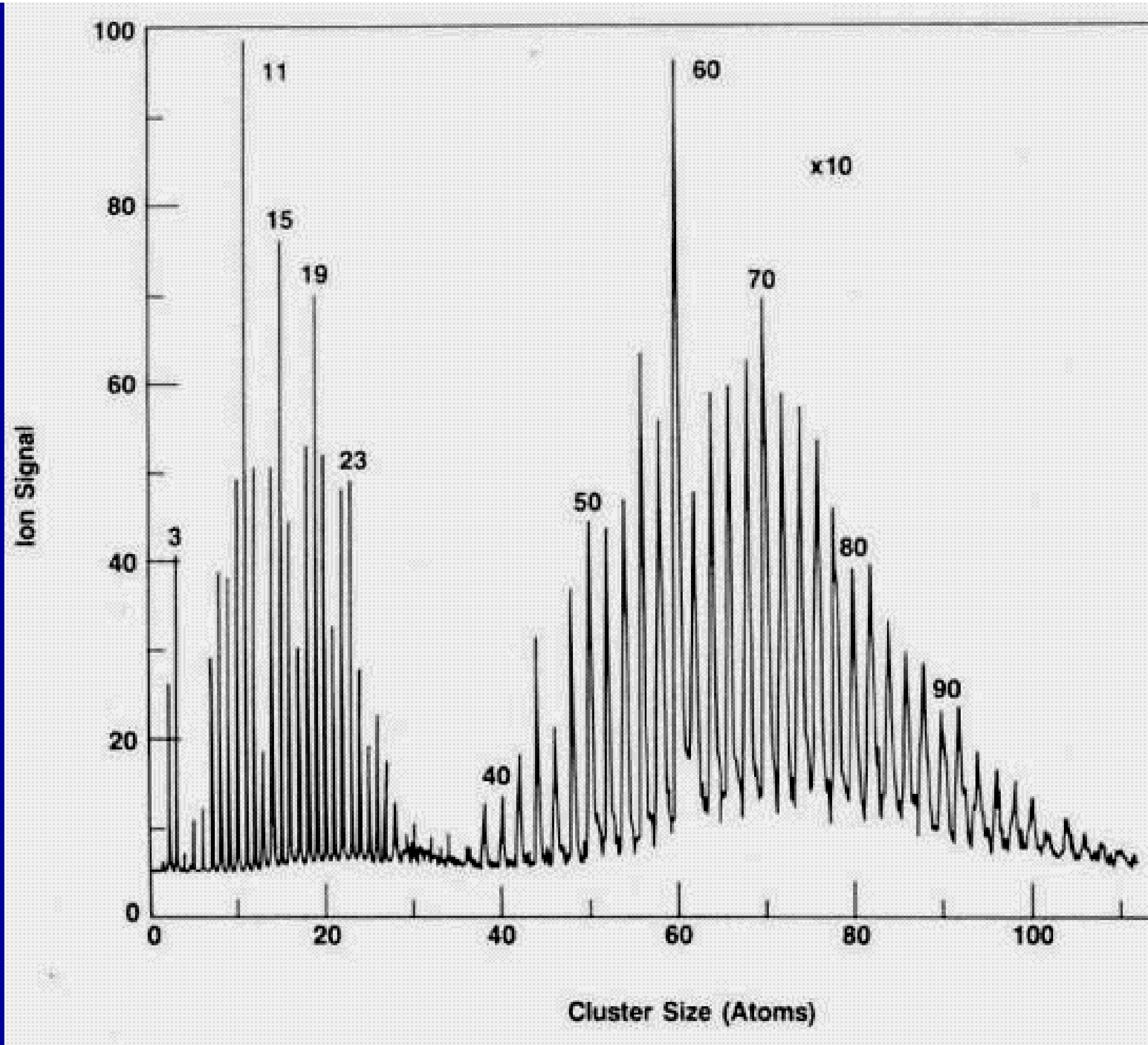
$3V = 5p + 6h$

$6(F - E + V) = p$

$$p = 12$$

$$V = 20 + 2h = 2(10 + h)$$

C_{20}, C_{24}, C_{26}, C_{28}, …, C_{60}, C_{70}, $C_{2(10+h)}$ …



clusters with *magic* even-numbers of carbon atoms 36 < n < 150 – fullerenes !!

E.A. Rohlfing, D.M. Cox, A. Kaldor, J. Chem. Phys. 81, 3322 (1984).

Euler's theorem for convex polyhedra

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$F = p + h$

where p and h are number of pentagonal and hexagonal faces, respectively

$2E = 5p + 6h$

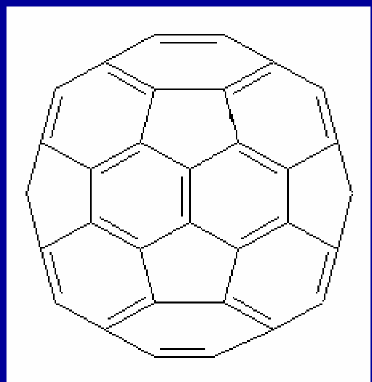
$3V = 5p + 6h$

$6(F - E + V) = p$

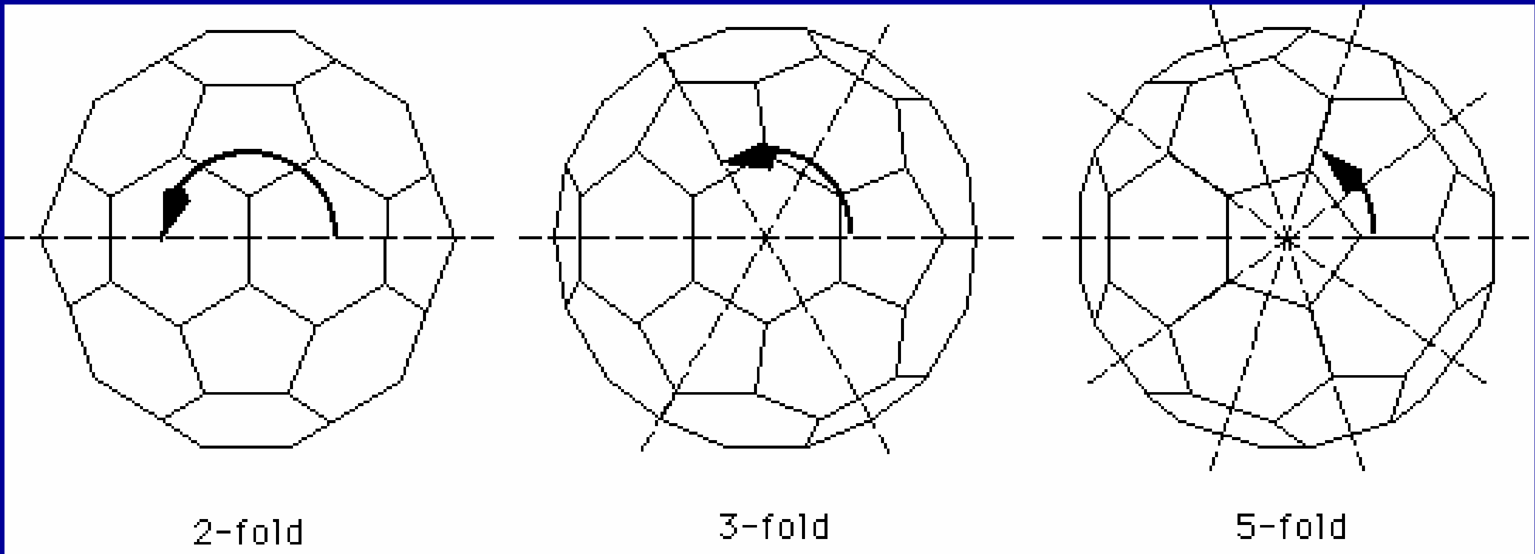
C_{20}, C_{24}, C_{26}, C_{28}, …, C_{60}, C_{70}, $C_{2(10+h)}$ …

$$p = 12$$

$$V = 20 + 2h = 2(10 + h)$$



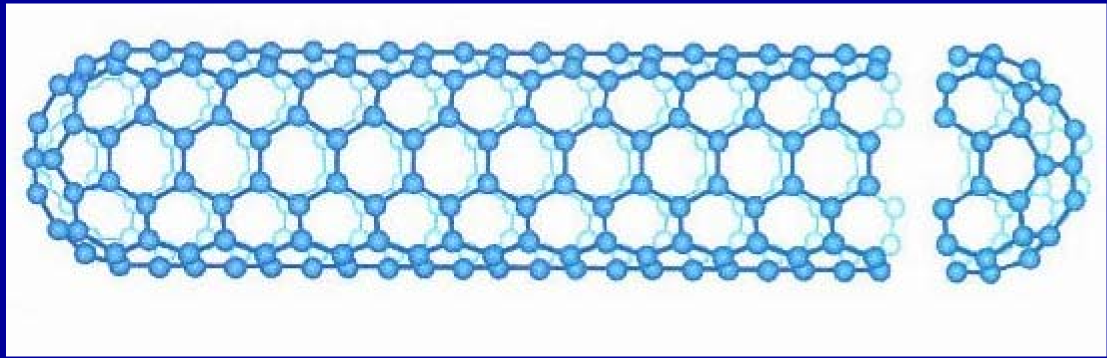
Isolated pentagon rule



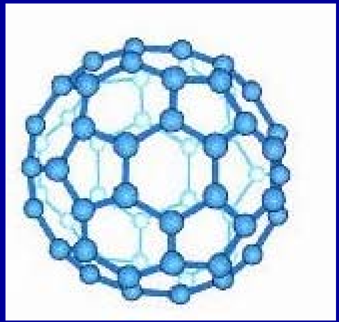
15 rotation axes **10 rotation axes** **6 rotation axes**

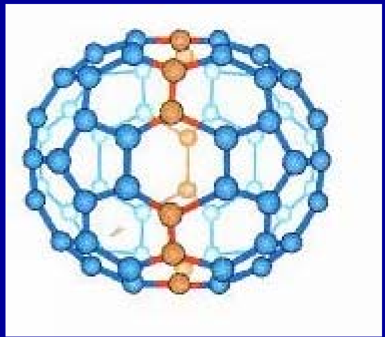
180° **120°** **360/5=72°**

$C_{1000000}$ - carbon nanotube

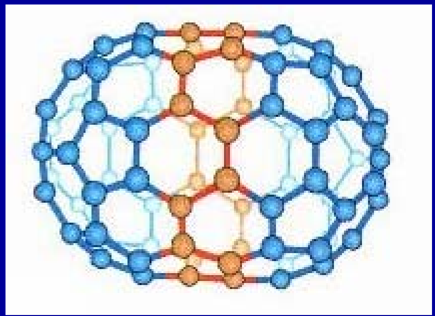


C_{60}



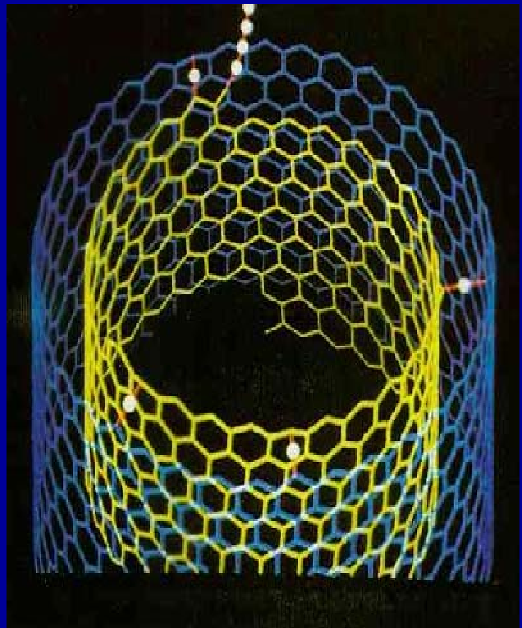


C_{70}



C_{80}

MWCN



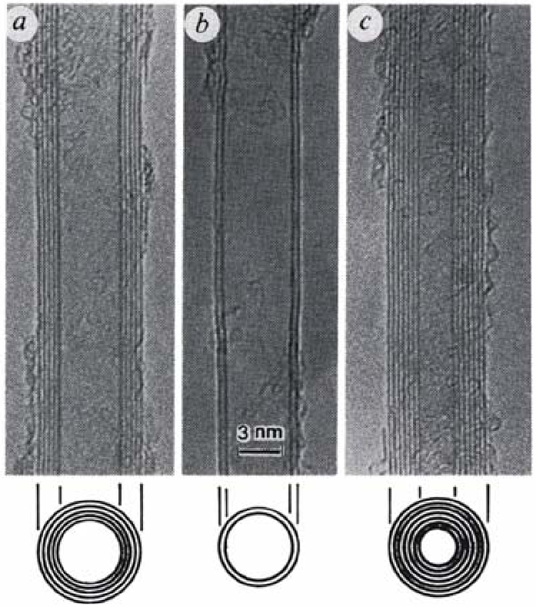
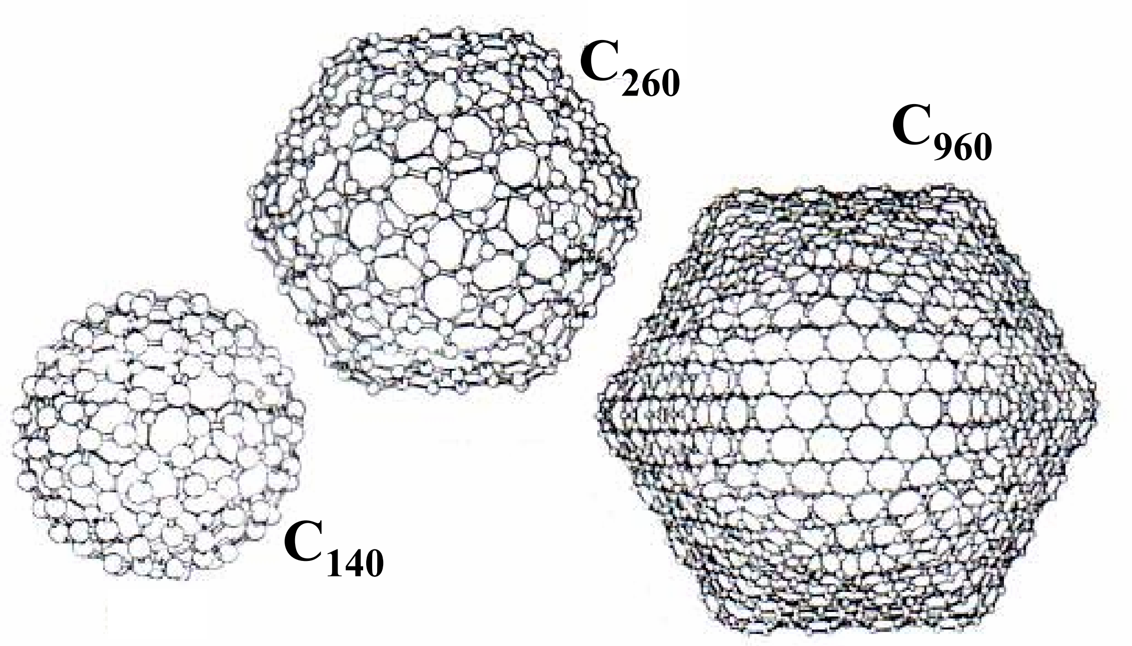


FIG. 1 Electron micrographs of microtubules of graphitic carbon. Parallel dark lines correspond to the (002) lattice images of graphite. A cross-section of each tubule is illustrated. *a*, Tube consisting of five graphitic sheets, diameter 6.7 nm. *b*, Two-sheet tube, diameter 5.5 nm. *c*, Seven-sheet tube, diameter 6.5 nm, which has the smallest hollow diameter (2.2 nm).

S. Iijima, Nature 354 (1991) 56

Giant fullerens with icosahedral symmetry



…One day I decided that we should build our own Buckminster Fuller domes, or rather molecular models of the giant fullerenes… Ken McKay… set about building C_{240}, C_{540} and later C_{960} and C_{1500} with icosahedral symmetry. When Ken came in with the model of C_{540} beautiful but I could not quite understand its shape – the model was not round like Buckminster Fuller's Montreal but had clear icosahedral tendencies. Indeed Ken's model had cusps focused at the 12 pentagons and from a distance had a definite polygonal outline… In fact as we looked more carefully at the infrastructure of Buckminster Fuller's domes we realized that the strut length in the vicinity of the pentagons had been adjusted to give them a smooth spheroidal shape.

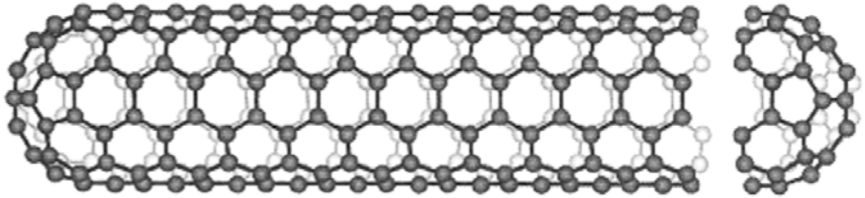
H.W. Kroto, Nobel Lecture, December 7, 1996

Carbon onions

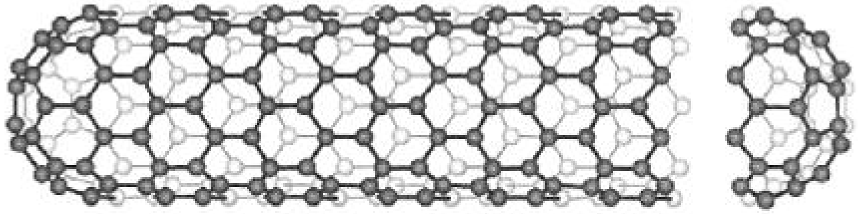
S. Iijima, J. Cryst.Crowth, 50, 675 (1980).

Three types of single-walled carbon nanotubes are possible depending on how the two-dimensional graphene sheet is rolled up with respect to its hexagonal lattice:

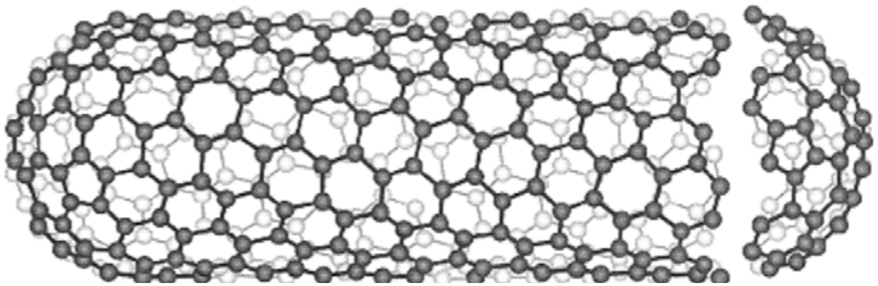
(1) *armchair* tubes (if C_{60} molecule is bisected normal to a fivefold axis)



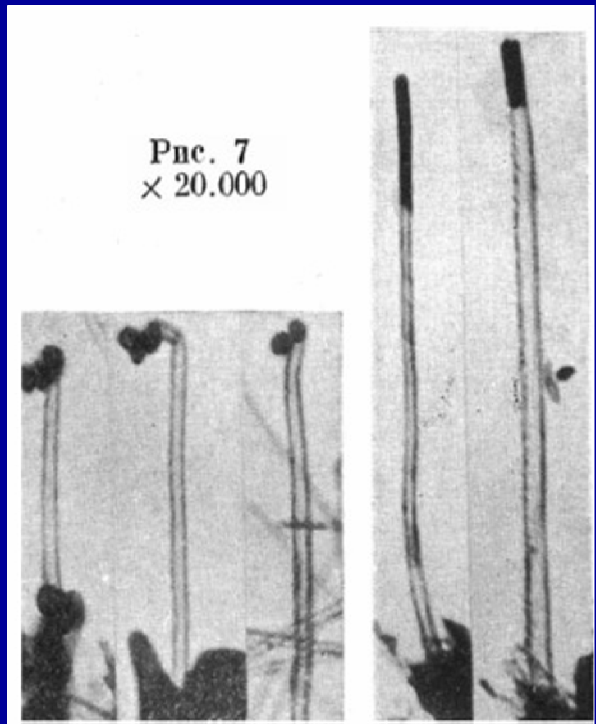
(2) *zigzag* nanotubes (if C_{60} is bisected normal to a threefold axis)



(3) a variety of *chiral* nanotubes with a screw axis along the axis of the tubule



L. V. Radushkevich and V. M. Luk’yanovich, Zhur. Fiz. Him. 26, 88 (1952) [in Russian] (*Chemical Abstracts*, 1953, v. 47, 6210e).



МЕТАЛЛЫ, № 3 · 1982

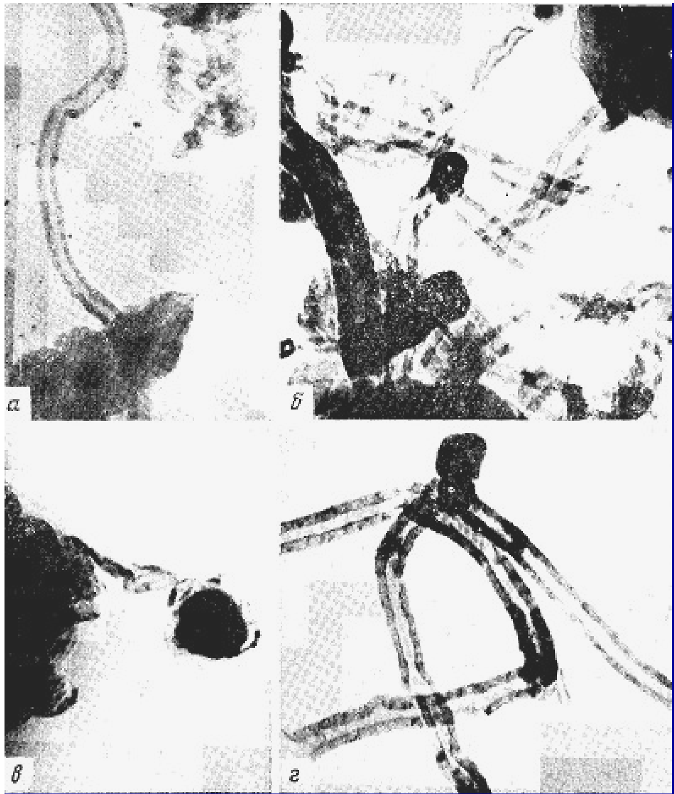
УДК 669.173.23

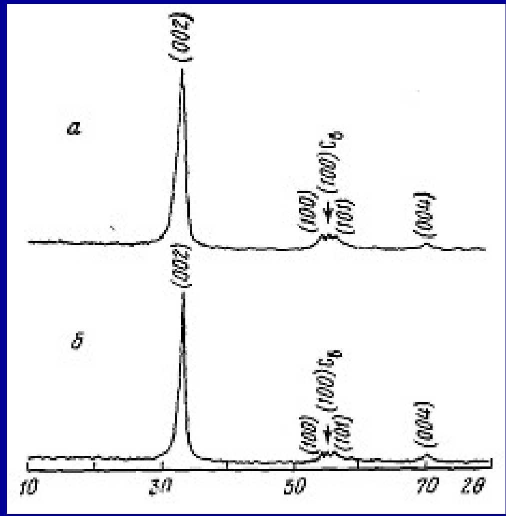
ОСОБЕННОСТИ ФАЗОВОГО СОСТАВА И СТРУКТУРЫ ПРОДУКТОВ ВЗАИМОДЕЙСТВИЯ NiO и Fe_2O_3 С ОКИСЬЮ УГЛЕРОДА

НЕСТЕРЕНКО А. М., КОЛЕСНИК Н. Ф., АХМАТОВ Ю. С., СУХОМЛИН В. И., ПРИЛУЦКИЙ О. В.

A. M. Nesterenko, N.F. Kolesnik, Yu.S. Akhmatov, V.I. Suhomlin, O. V. Prilutskii, "Characteristics of the phase composition and structure of products of the interaction of nickel (II) and iron (III) oxide with carbon monoxide". *Izv. Akad. Nauk SSSR*, Met. 1982, 3, 12-17 [in Russian].

***Chemical Abstracts*, 1982, v. 97, 201884t.**

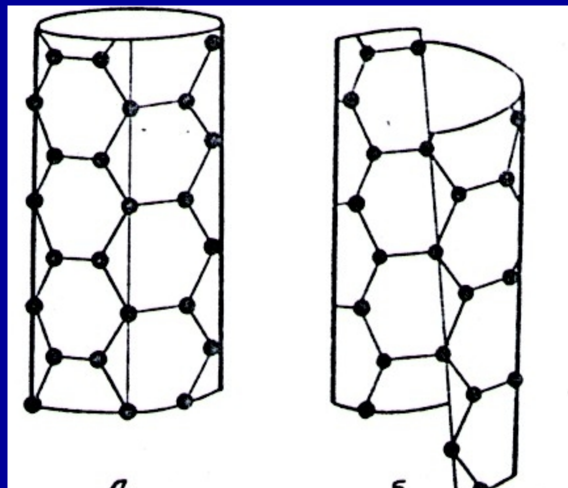




XRD pattern

“Carbon multi-layer tubular crystals” are formed by rolling graphene layers into cylinders

TEM: ×2500-100000



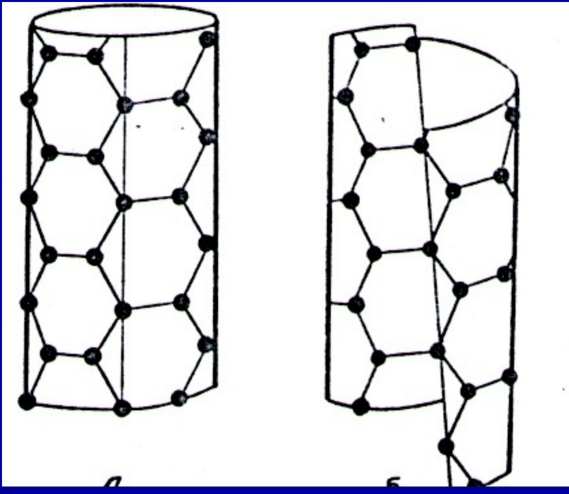
Фиг. 6. Схематическое изображение вариантов замыкания моноатомных гексагональных сеток графита (002) при образовании цилиндрических трубчатых кристаллов: *а* — круговое замыкание плоской сетки; *б* — замыкание с образованием однозаходной спирали (шаг спирали равен периоду *а* решетки графита)

A. M. Nesterenko, N.F. Kolesnik, Yu.S. Akhmatov, V.I. Suhomlin, O. V. Prilutskii, ***Izv. Akad. Nauk SSSR*****, Met. 1982, 3, 12-17**

A. M. Nesterenko, N.F. Kolesnik, Yu.S. Akhmatov, V.I. Suhomlin, O. V. Prilutskii, *Izv. Akad. Nauk SSSR*, Met. 1982, 3, 12-17

Hypothesis on chirality

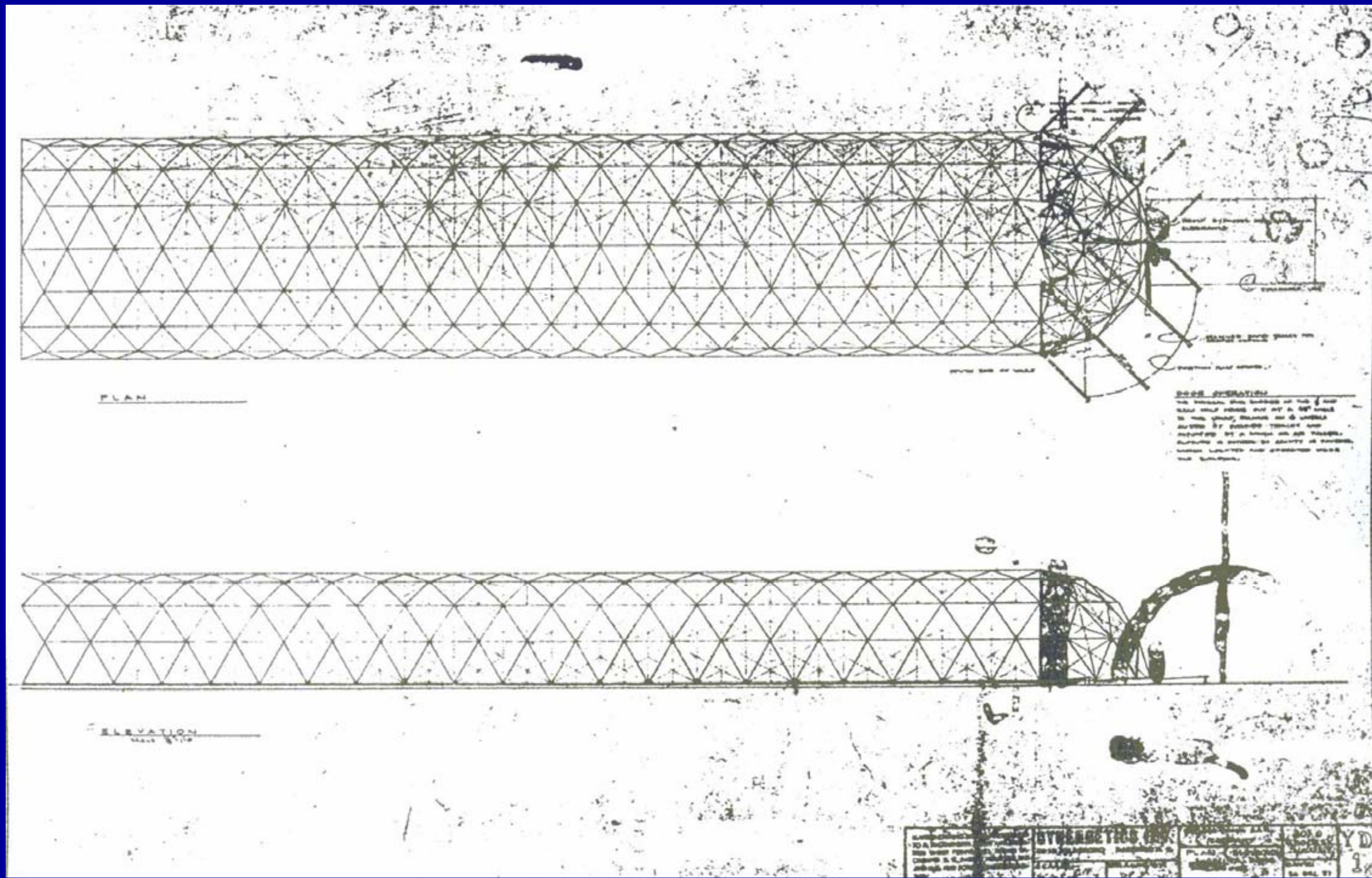
"Carbon multi-layer tubular crystals" are formed by rolling graphene layers into independent cylinders: many different arrangements of graphene hexagonal nets are possible



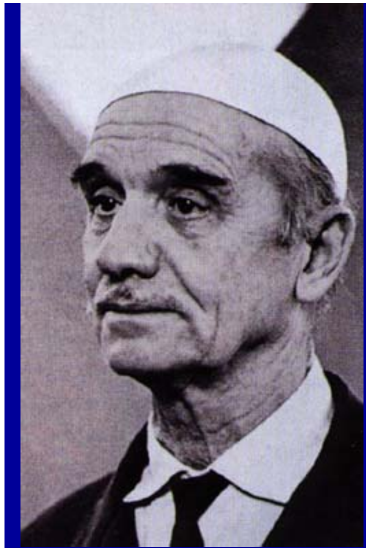
Фиг. 6. Схематическое изображение вариантов замыкания моноатомных гексагональных сеток графита (002) при образовании цилиндрических трубчатых кристаллов: *а* — круговое замыкание плоской сетки; *б* — замыкание с образованием однозаходной спирали (шаг спирали равен периоду *а* решетки графита)

Circular arrangement (armchair tube)

Arrangement along a spiral (helical or chiral tube)



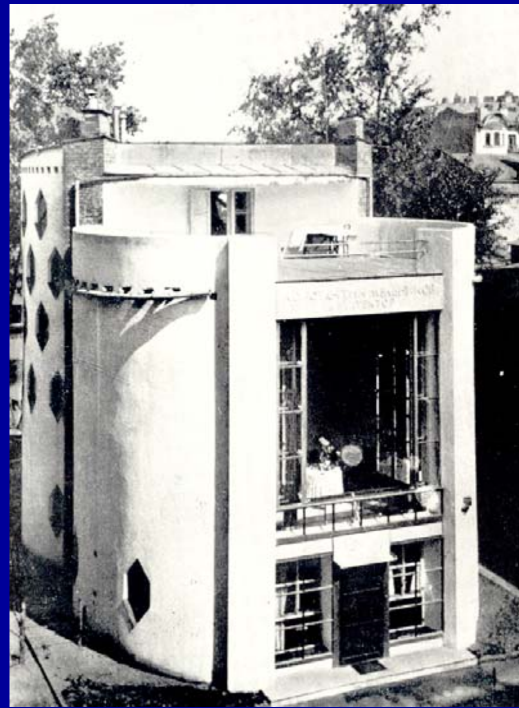
Buckminster Fuller's design for the entrance pavilion of the Union Tank Car Company

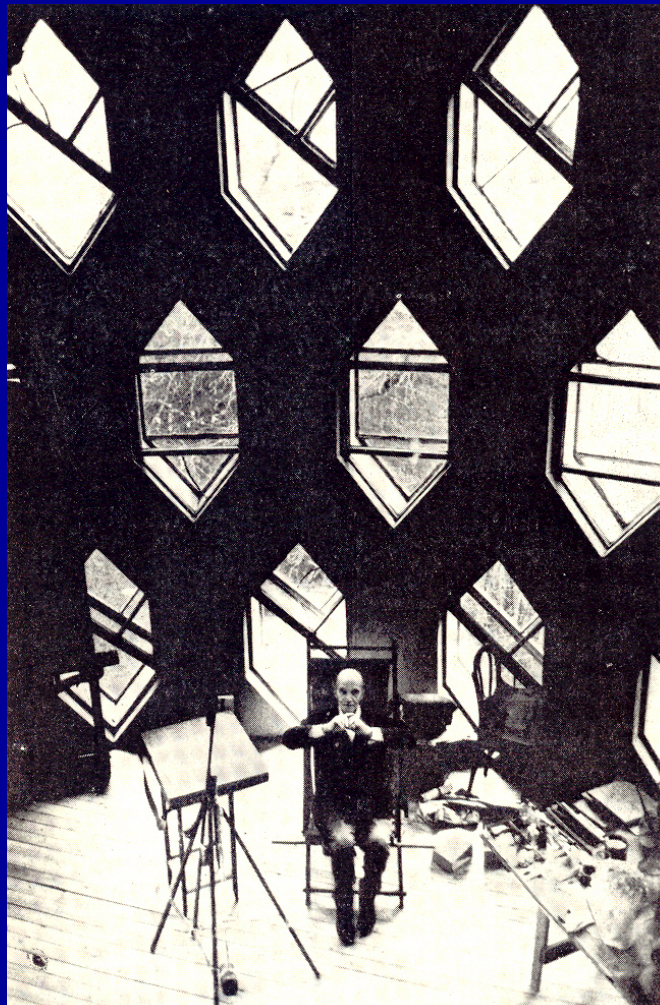


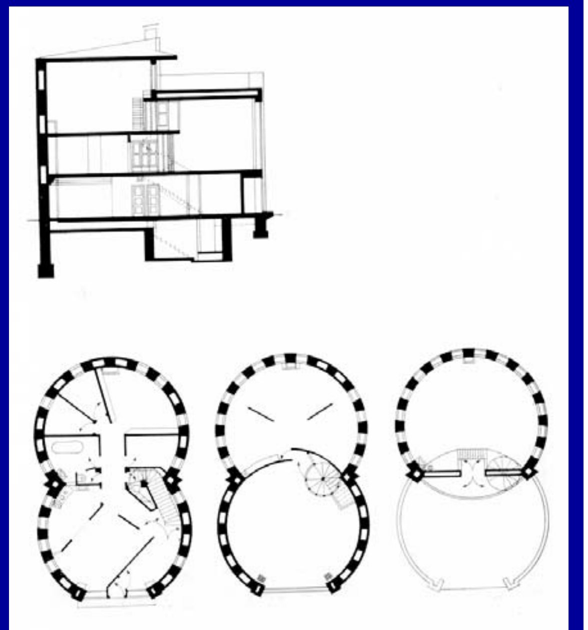
Konstantin Melnikov

1890-1974

1927

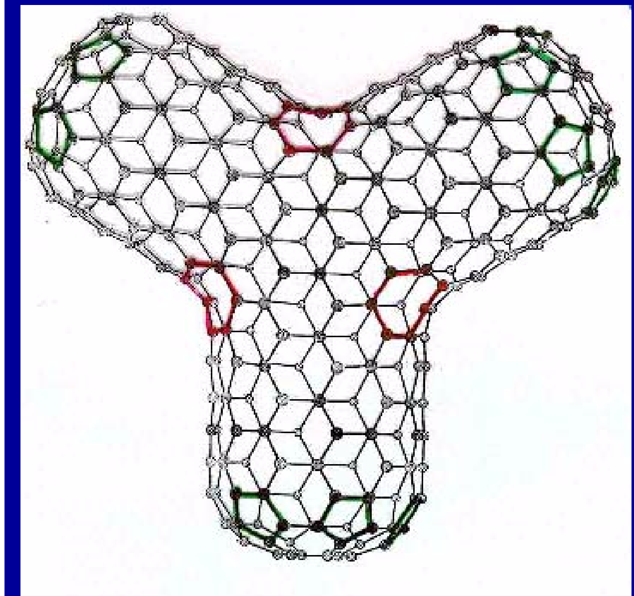




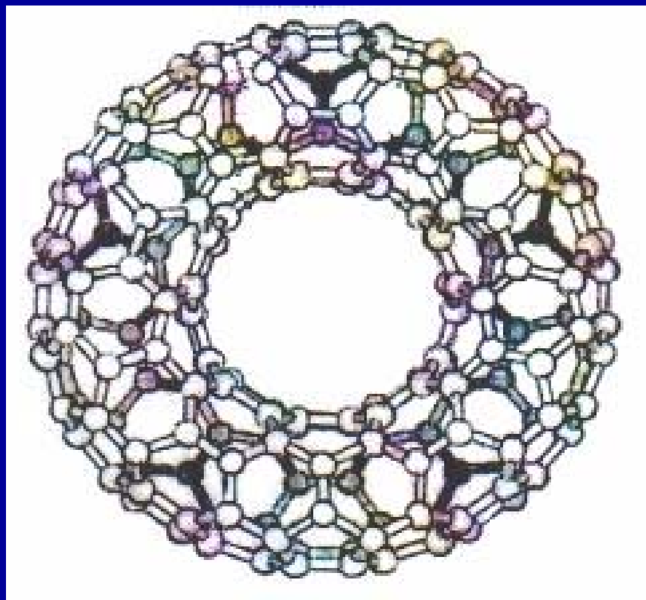


Fullerene-like structures with a negative curvature

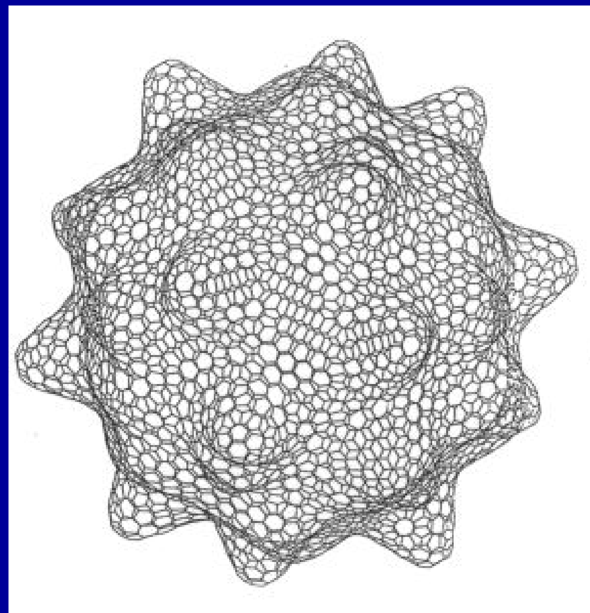
Pentagons, heptagons, hexagons



Y-nanotube

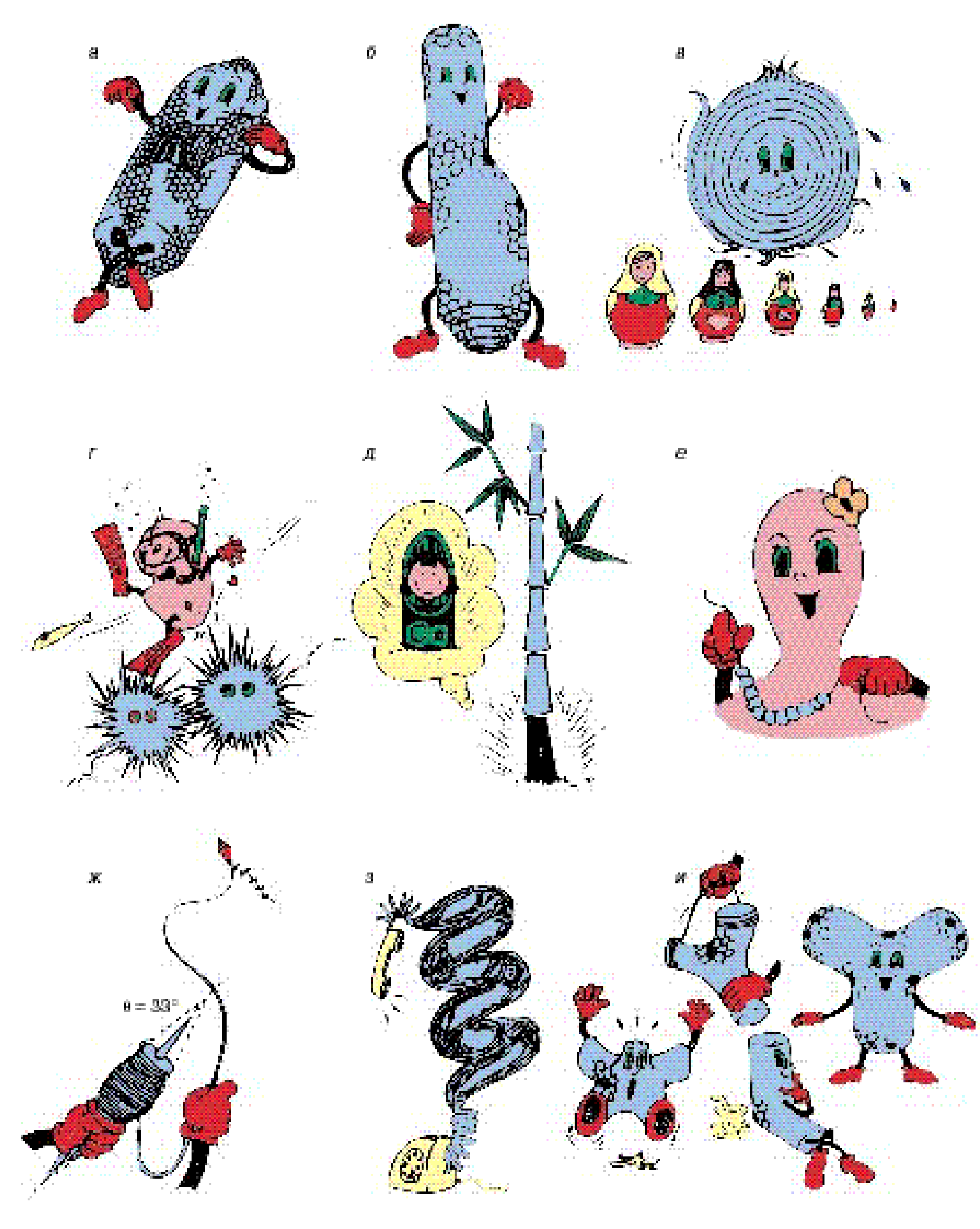


Carbon nano-torus



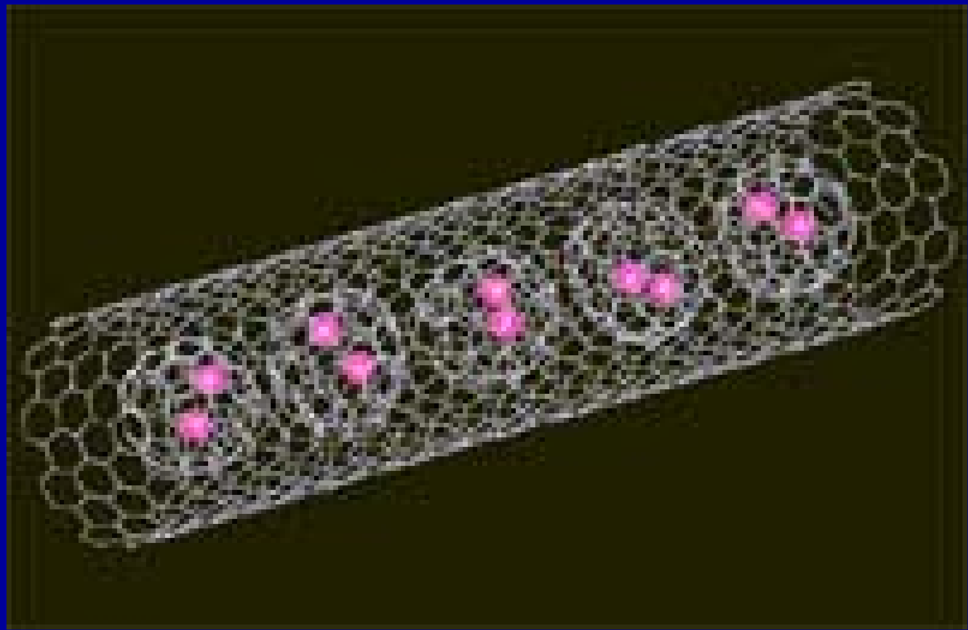
Star-like cluster

E. Osawa et. al.,MRS Bull. 19 (11), 33 (1994).



Comical representation of various forms of nanocarbons:
a) Tube with both ends closed,
b) Tube with various diameter,
c) Buckyonion,
d) Sea urchins,
e) Bamboo-like nanotube,
f) Necklaces with buckyonion beads,
g) Spinning cones,
h) Helical telephone coils,
i) Connectors and treapods

Carbon nanopeapod



HRTEM,

$Sc_2@C_{84}$

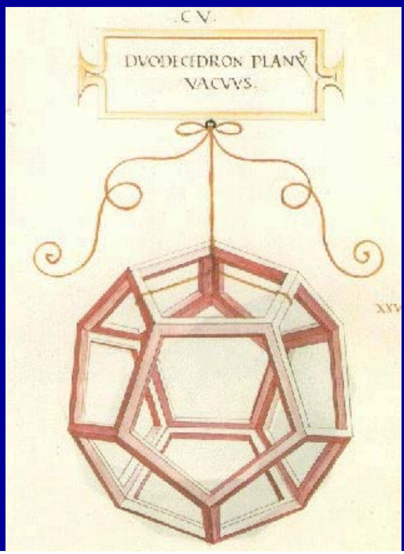
K. Suenaga, T. Okazaki, C.-R. Wang, S. Bandow, S. Shinohara and S. Iijima, *Phys. Rev. Lett.* 90, 055506 (2003).

Small fullerenes (with V<60) do not satisfy to "isolated pentagon rule" and are chemically unstable

C_{36} (p=12, h=8)- C. Piskoti, J. Yarger and A. Zettl, *Nature* <u>393</u>, 771 (1998).

Special conditions of graphite vaporization

C_{20} (p=12, h=0) - H. Prinzbach, A. Weiler, P. Landenberger, F. Wahl, J. Worth, L. Scott, M. Gelmont, D. Olevano, B. Issendorff, *Nature* <u>407</u>, 60 (2000).



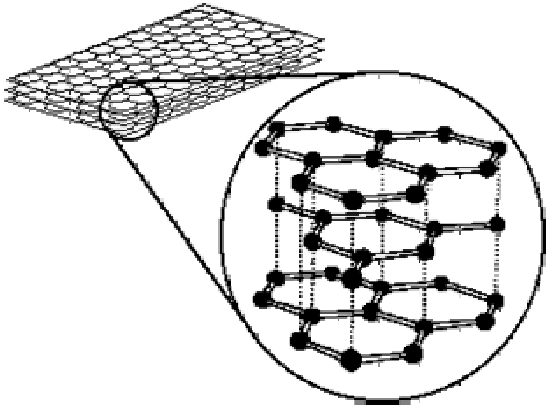
Multi-step organic chemical synthesis:

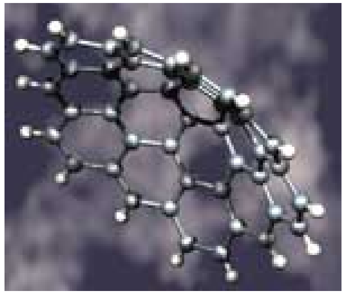
$C_{20}H_{20} \rightarrow C_{20}Br \rightarrow C_{20}$

Is it possible to build fullerenes from other elements?

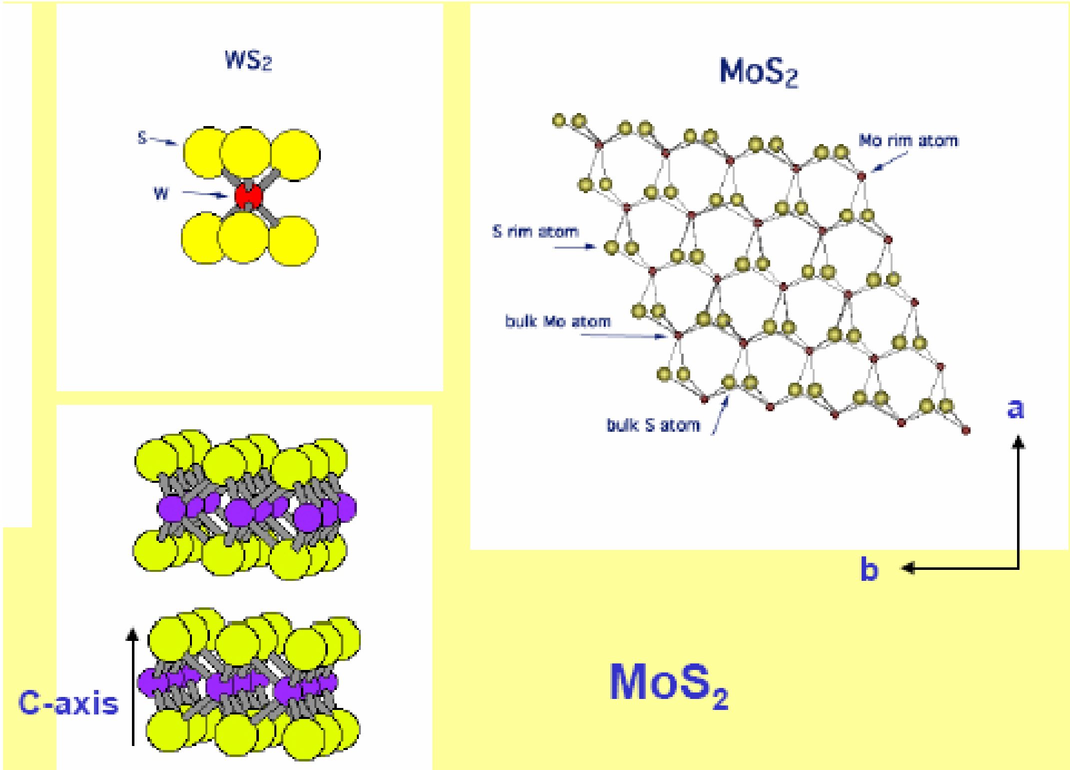
Non-carbon (inorganic) fullerenes?

Inorganic nanotubes and fullerene-like particles from 2-D layered compounds



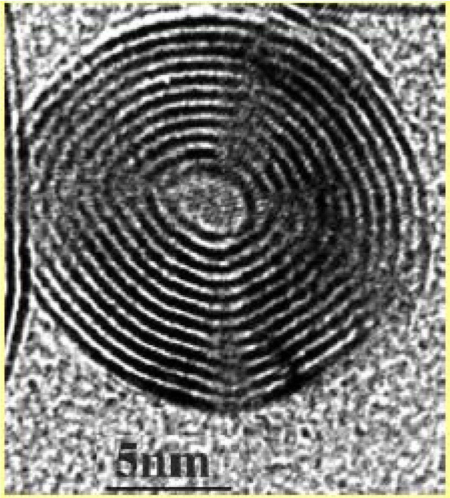


Graphite

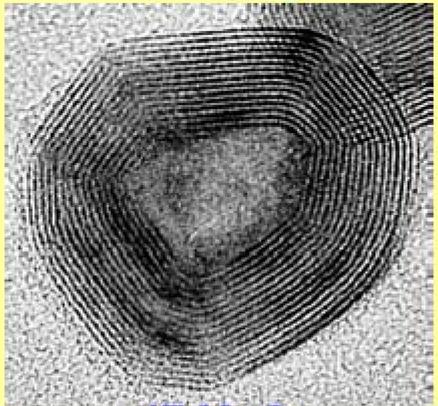


R.Tenne and co-workers, *Nature*, 360, 444 (1992); 365, 113 (1993); *J. Am. Chem. Soc.*, 116, 1914 (1994); *Science*, 267, 222 (1995)

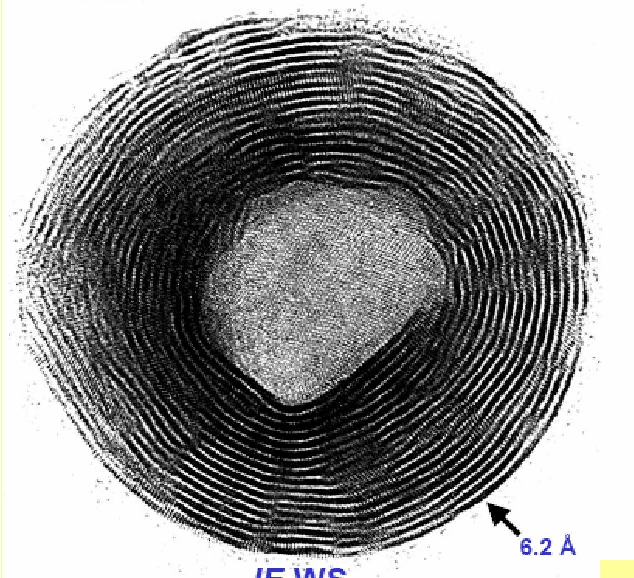
L. Margulis, M. Genut, G. Hodes, G. Salitra, M. Talianker, L. Gheber, M. Hershfinkel, J.L. Hutchison, V. Volterra, Y. Feldman, E. Wasserman, D.J. Srolovitz



IF-WS_2

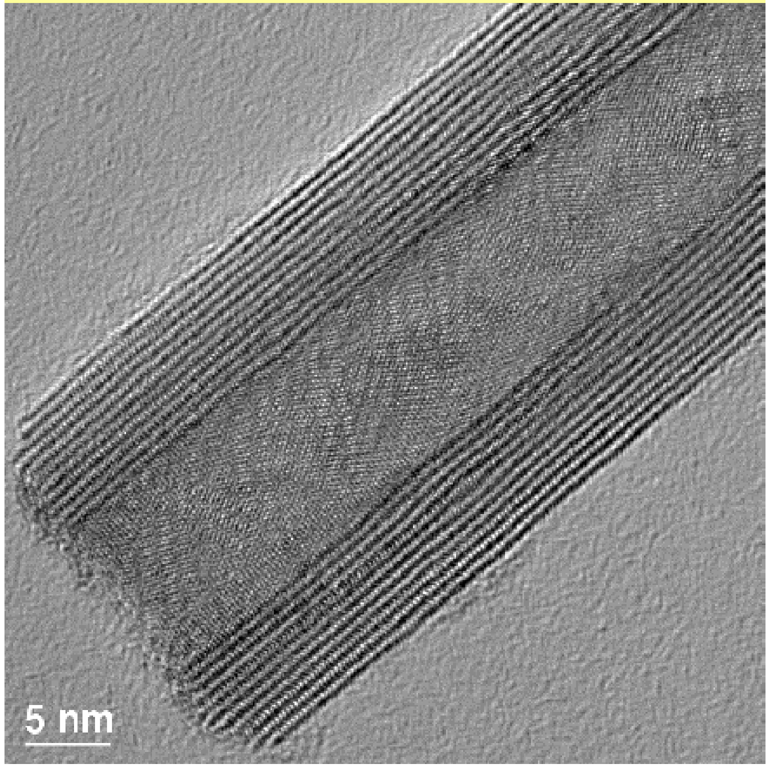


IF-MoS_2



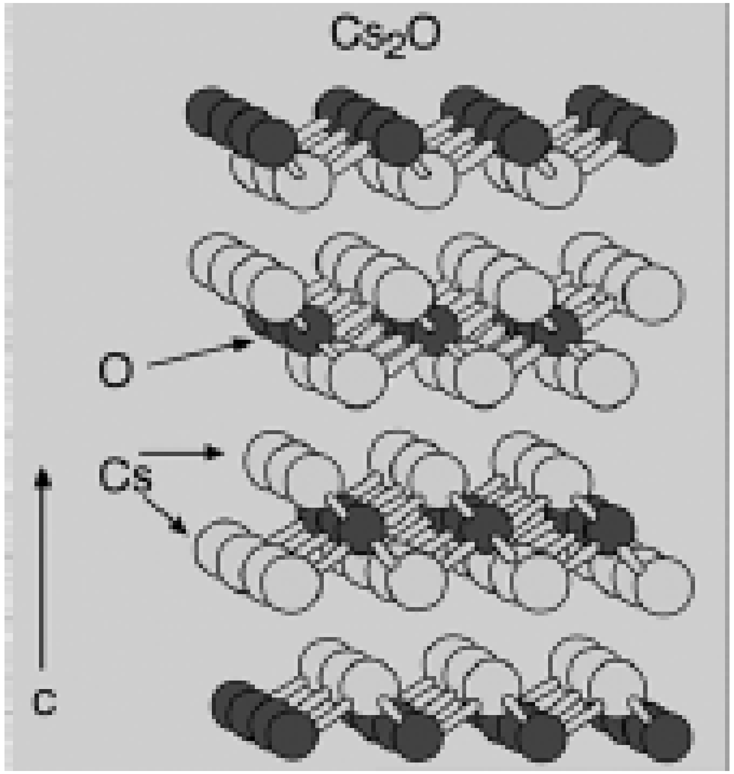
IF-WS_2

Multiwall WS_2 nanotube



Cs_2O

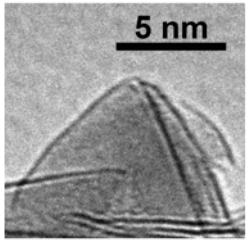
Applications in: photoemissive systems, photocathodes, negative electron affinity devices, image intensifiers, discharge lamps, television cameras, lasers.

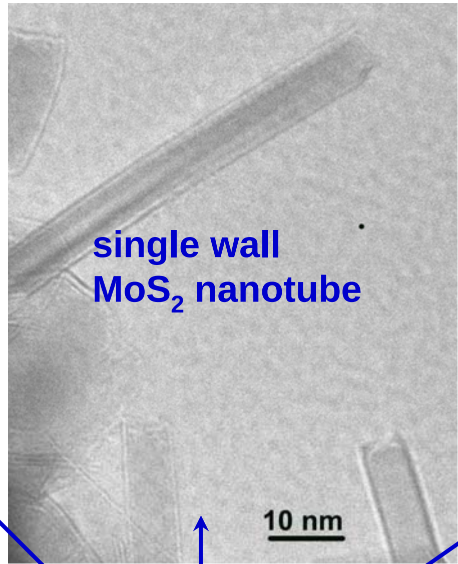


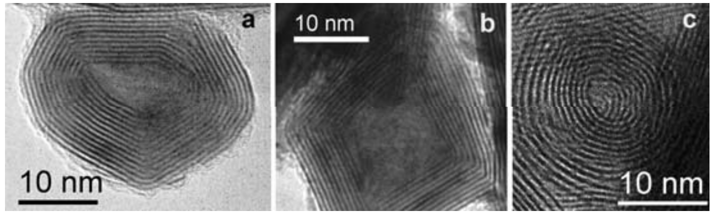
Extremely reactive.

Inorganic (non-carbon fullerenes)

MoS_2 fullerene-like nanoparticle



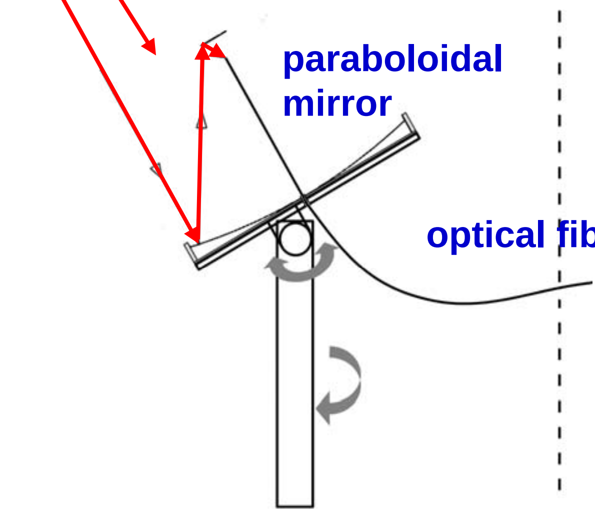




Nested Cs_2O fullerenes

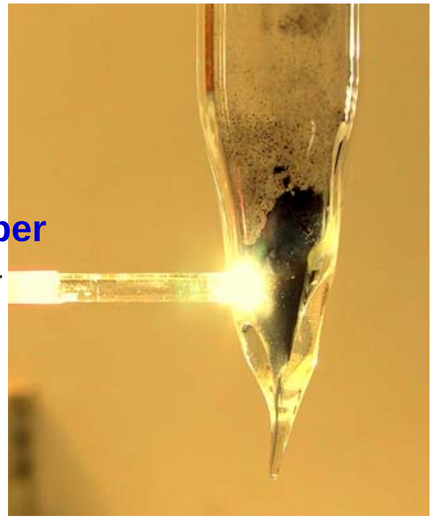
Albu-Yaron, T. Arad, M. Levy, R. Popovitz-Biro, R. Tenne, J. M. Gordon, D. Feuermann, E. A. Katz, M. Jansen and C. Mühle. ***Advanced Materials***, 18, 2993 (2006).

Solar assisted synthesis



paraboloidal mirror

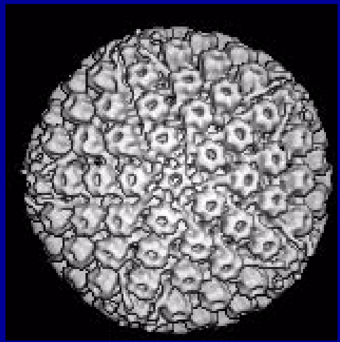
optical fiber

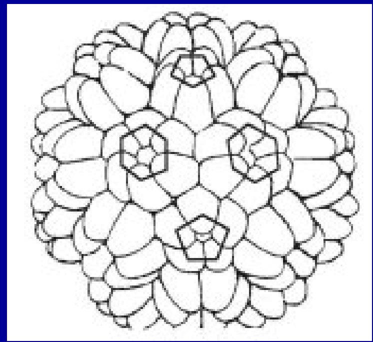


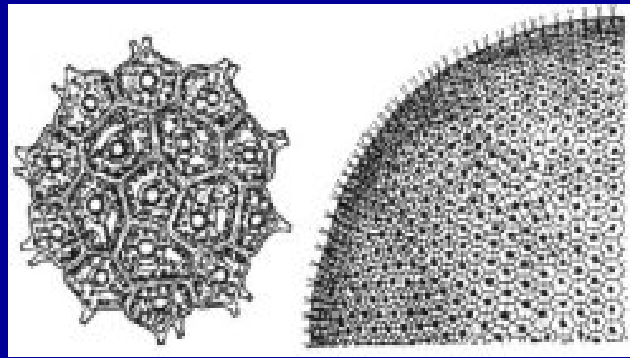
J. M. Gordon, E. A. Katz, D. Feuermann, A. Albu-Yaron, M. Levy, R. Tenne. ***Journal of Materials Chemistry***, 18, 458 (2008).

Fullerene-like structures in animate nature

Fullerene-like viruses







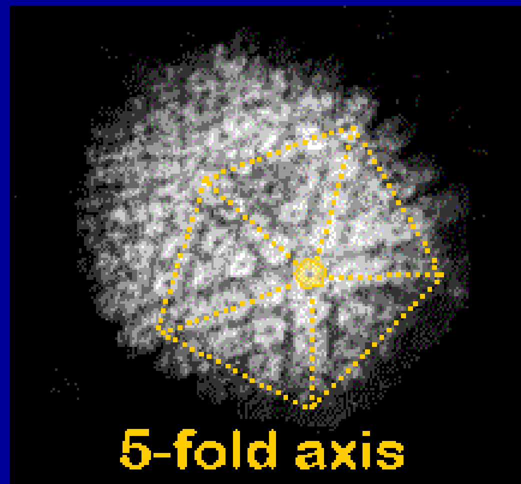
20-300 nm

Herpes

Could viruses be considered as living organisms?

Yes: they have genetic material (DNA, RNA) and can reproduce themselves

No: they have no cell structure

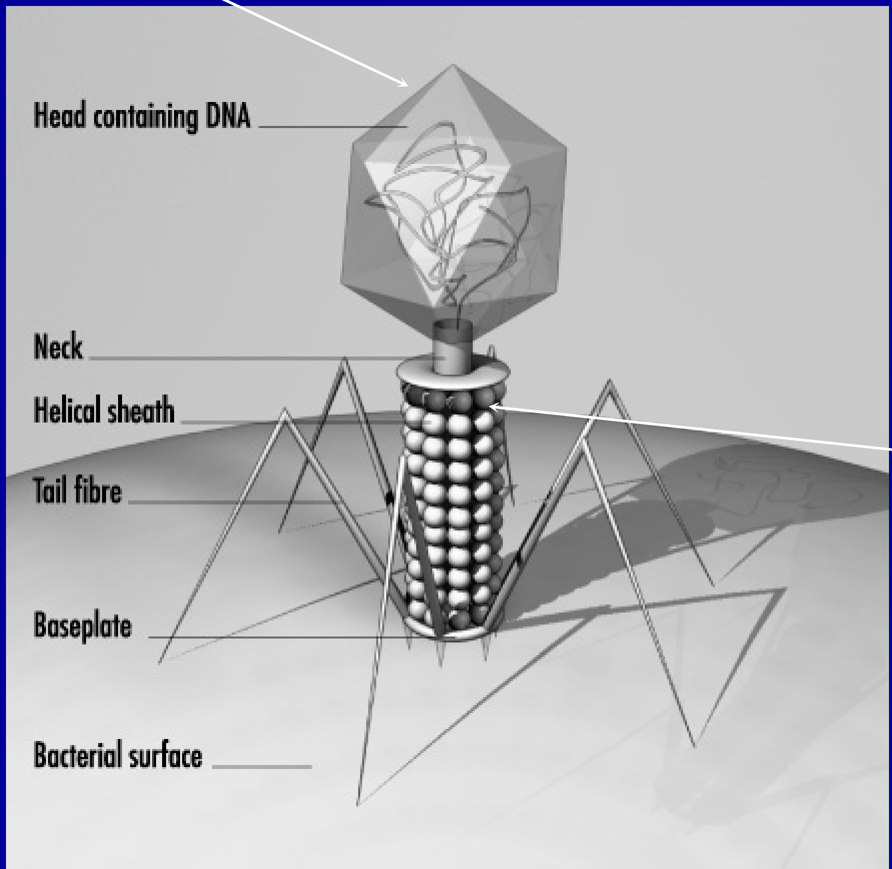


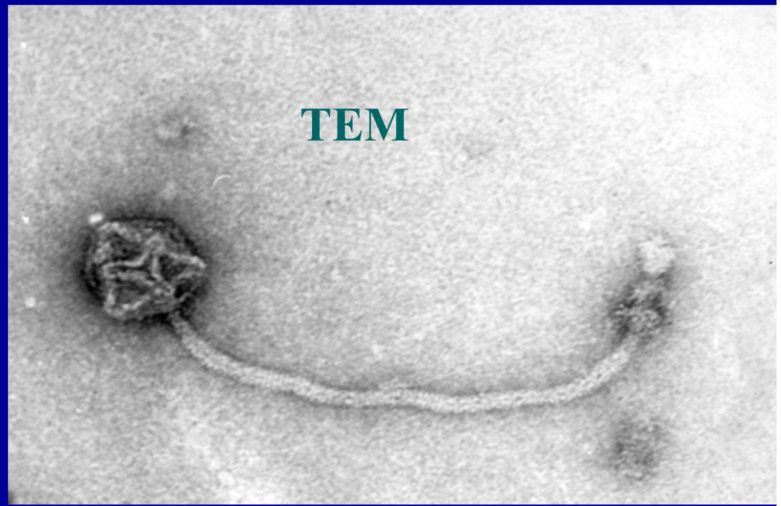
Viruses are on the very boundary between animate and abiotic nature.

Bacteriophages – or **phages** - from 'bacteria' and Greek phagein, 'to eat') - viruses that infect bacteria.

Discovered by Félix d'Hérelle, 1917

40-140 nm





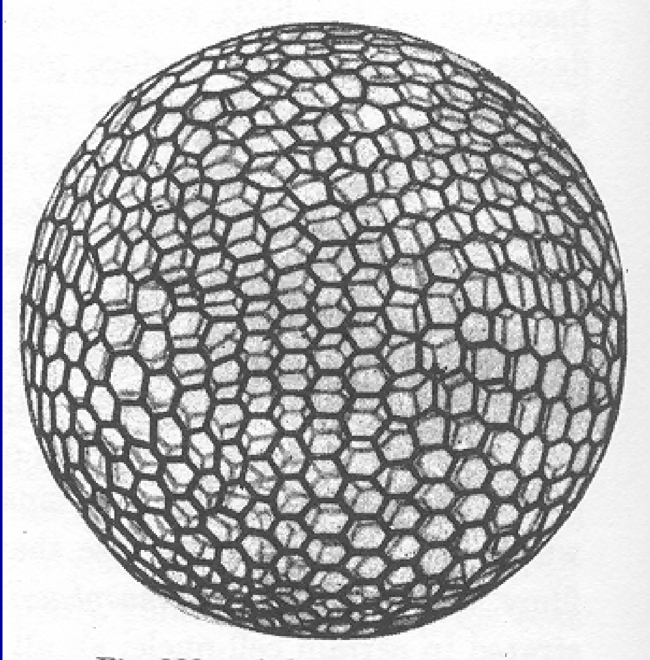
Nanotubes (10-40 nm diameter, 100-200 nm length)

Phage inject its DNA to a bacterial cell and suppress its DNA

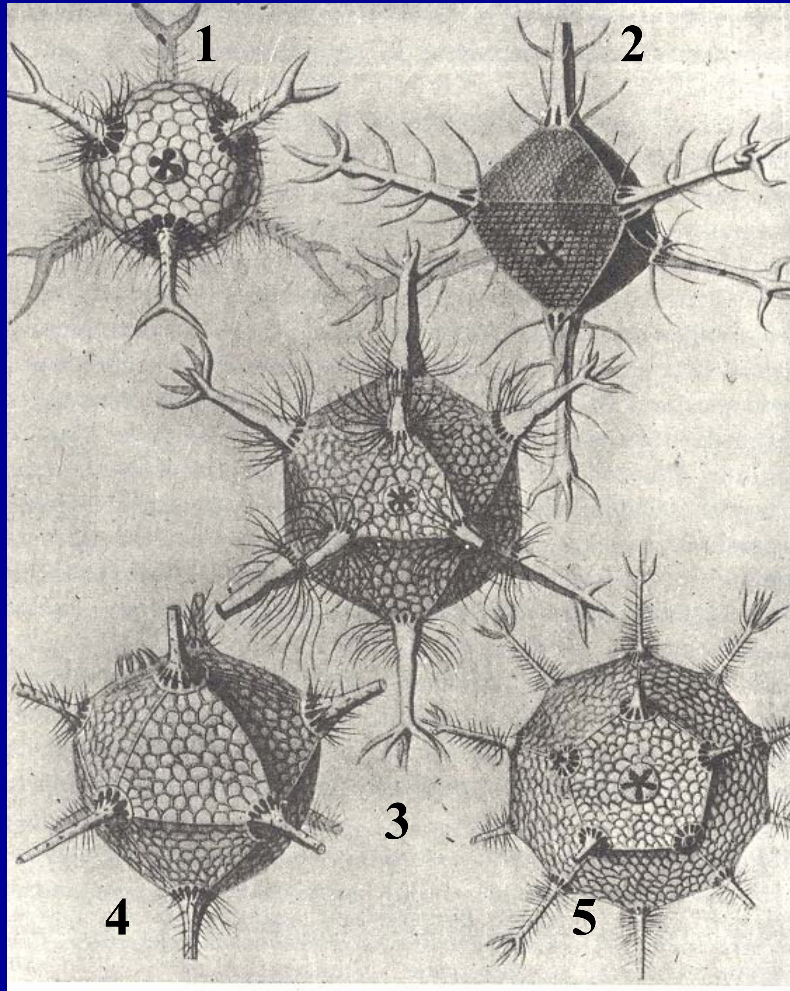
Phage therapy

Radiolaria

40 μ m – 1mm

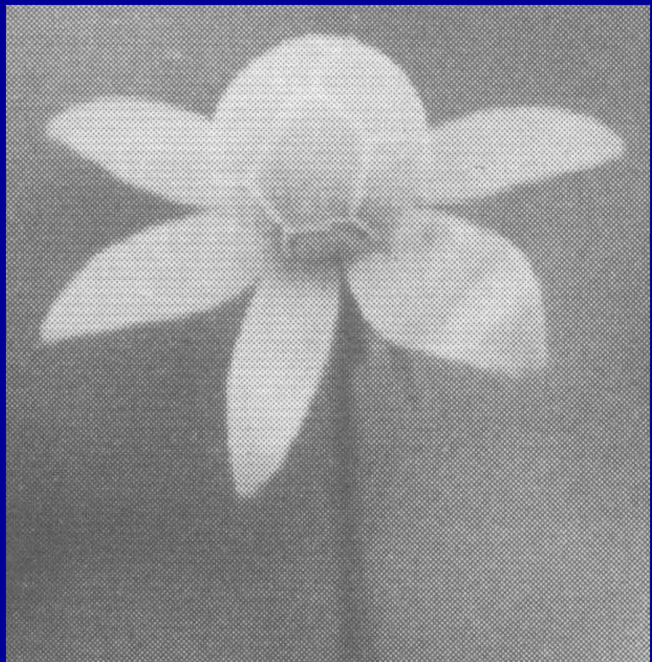


Skeleton of *Aulonia hexagona Hkl.*
From: D'arcy W. Thomson "On Growth and Form", Cambridge Univ. Press, 1917



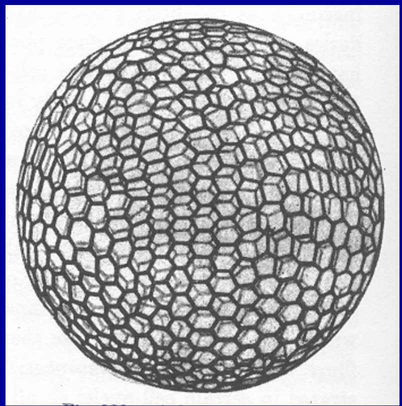
Skeletons of various radiolarians: 1. *Cicroporus sexfurcus*, 2. *C. octahedrus*, 3. *Circogonia icosahedra*, 4. *Cicrospathis novena*, 5. *Cicrorrhegma dodecahedra*.
From: E. Haeckel "Monograph of the Challenger Radiolaria", 1987.

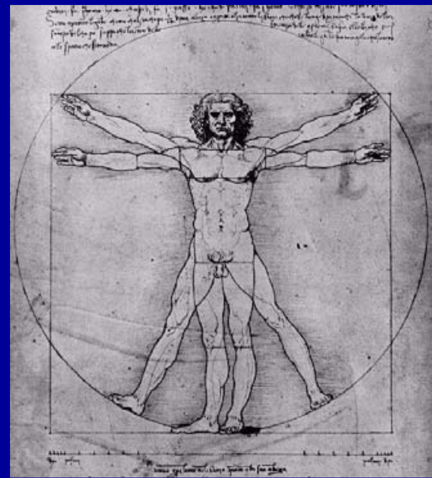
Fullerene-like structures in plants



Capsule of *Trientalis europaea*

Evolution of living organisms



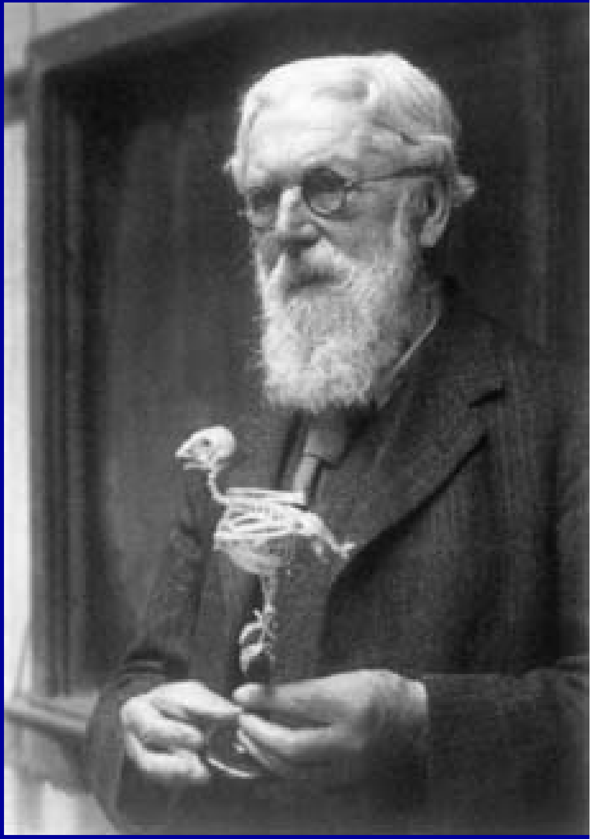


Decrease of symmetry

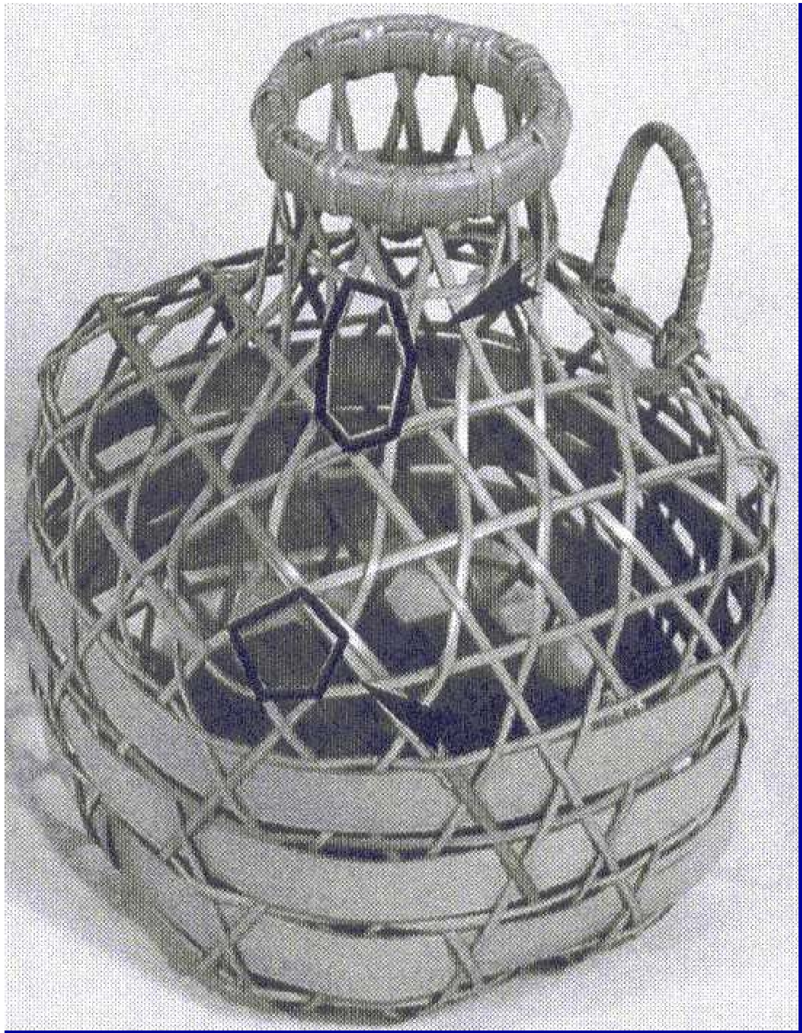
$F - E + V = 2$ $p = 12$ $V = 20 + 2h = 2(10 + h)$

Carbon clusters:
D.E.H. Jones, 1966 → S. Iijima, 1980 → H. Kroto, 1985-1992

Radiolaria:
D'arcy W. Thomson "On Growth and Form", Cambridge Univ. Press, 1917

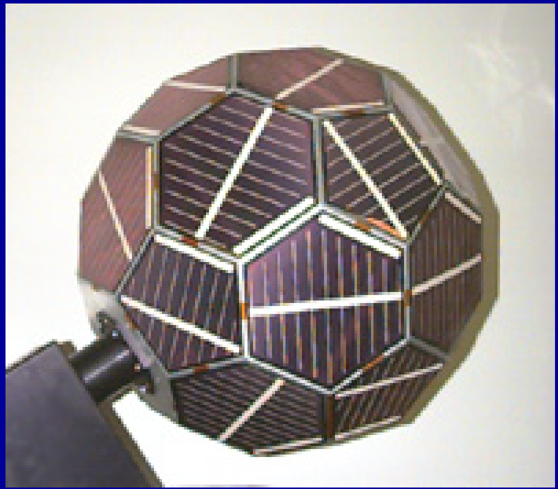


Scientific relay race:
D'arcy Thomson → Jones → Iijima → Kroto



Japanese bamboo vase

High resolution high efficiency gamma ray detector. It consists of a “spherical” shell of 110 Ge detectors. Lawrence Berkeley National Laboratory.



PowerSphere nanosatellite, The Aerospace Corporation, NASA