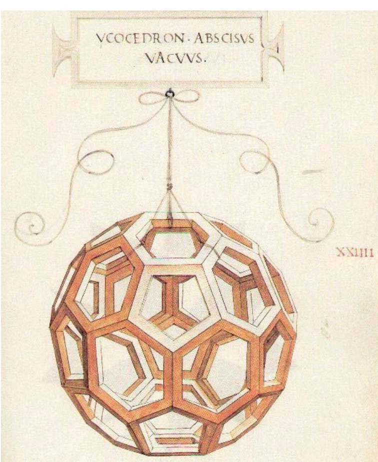
Fullerene-like architecture in nano-, micro- and macro-worlds

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

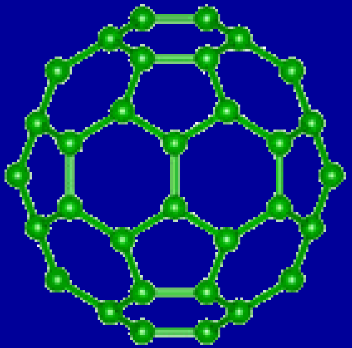
Contents

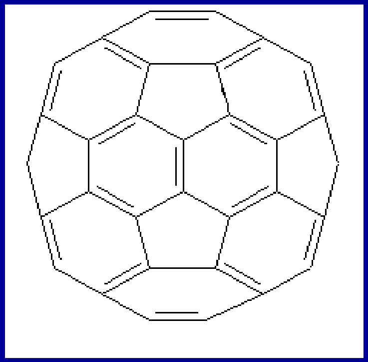
1. Discovery of C_{60} molecule
2. Buckminster Fuller's energetic geometry and geodesic domes
3. Long history of exploration of polyhedra: science and fine art
4. Leonhard Euler's theorem
5. Fullerene-like structure of molecules and nanoclusters, viruses, microorganisms and buildings: the same story

Allotropes of carbon

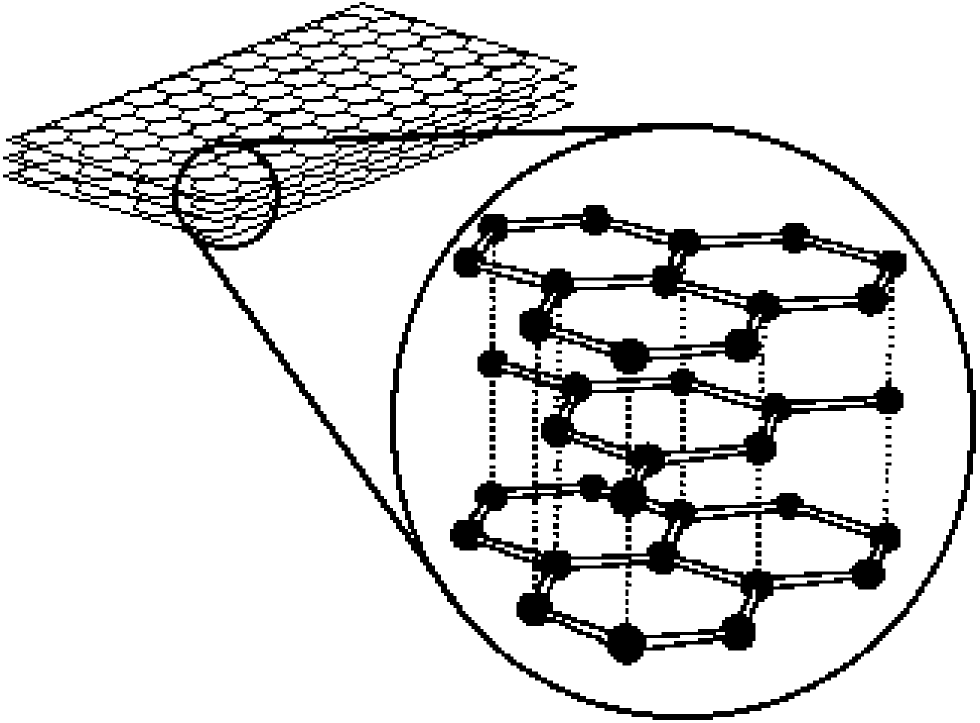
Graphite and diamond

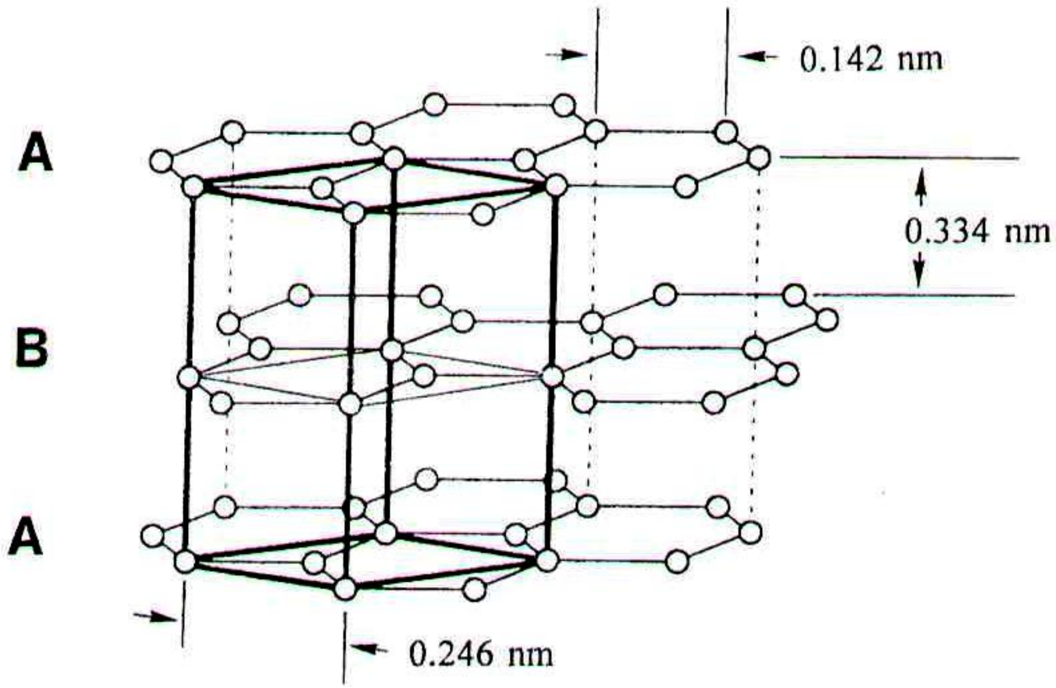
C_{60}





1985



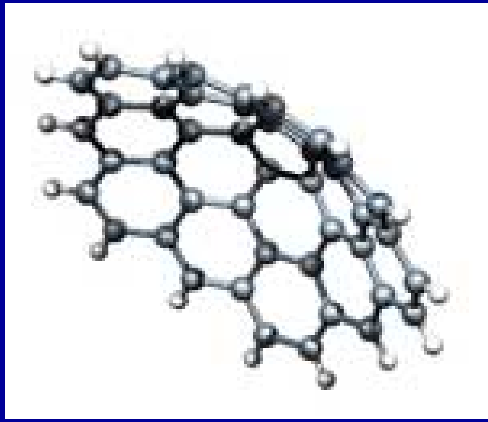


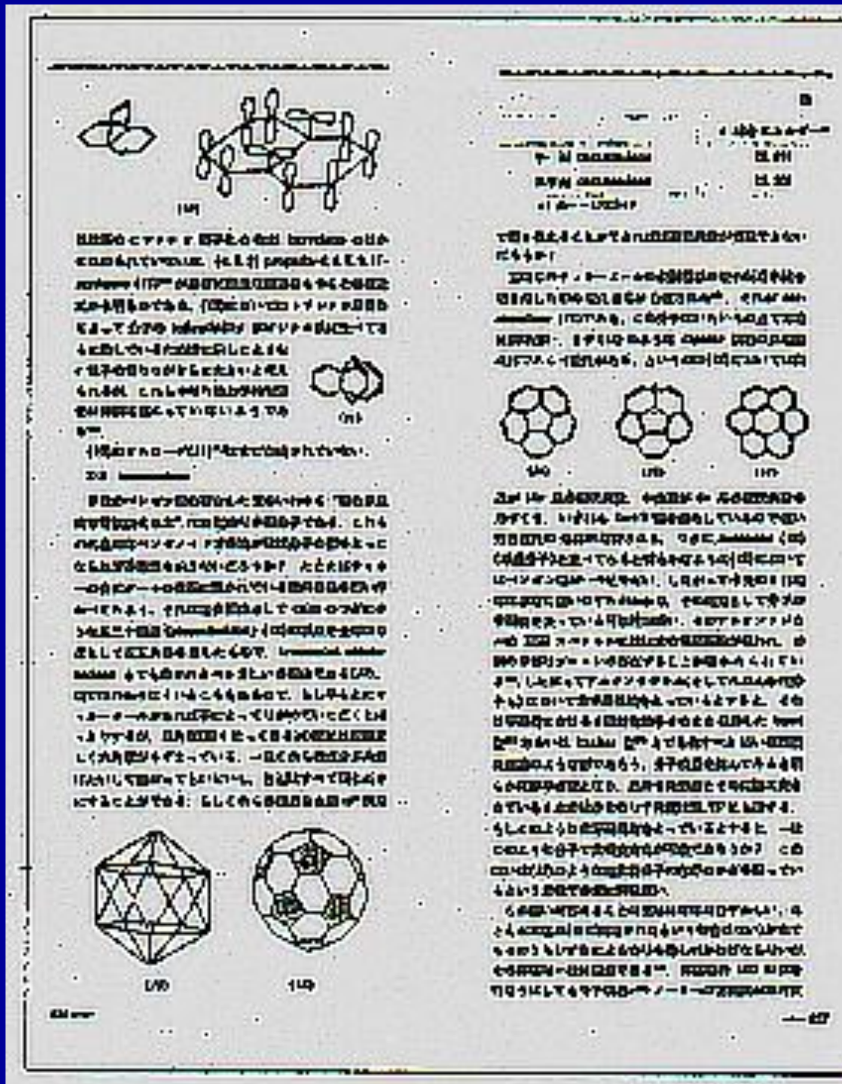
Crystalline structure of graphite

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

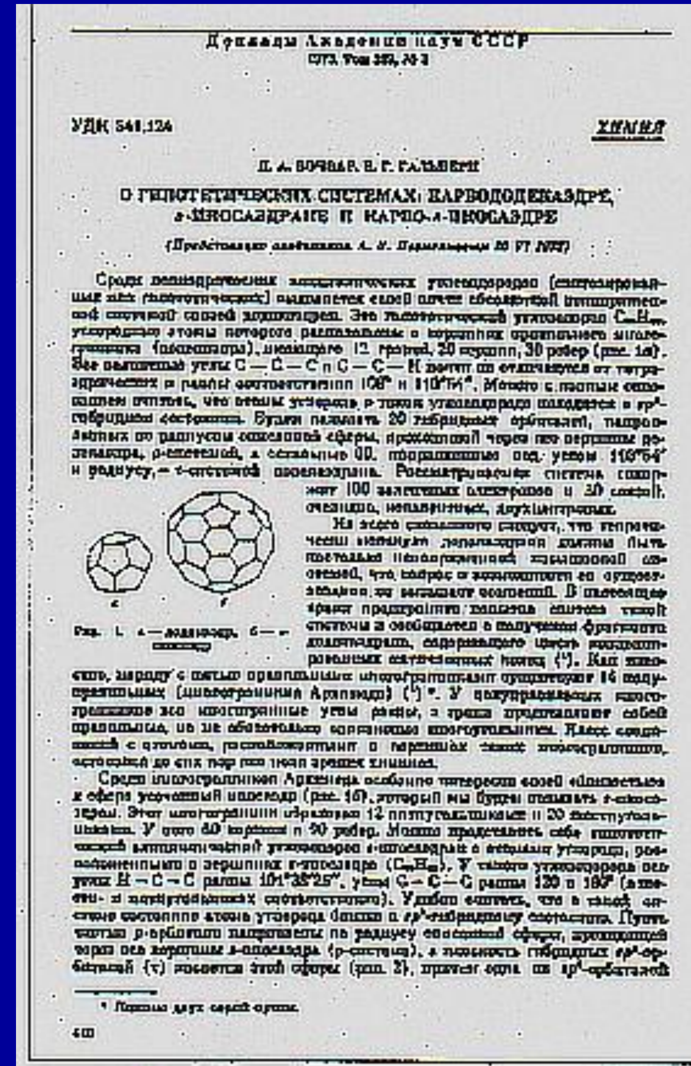
D. E. H. Jones, The Inventions of Daedalus (W. H. Freeman, Oxford, 1982).

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

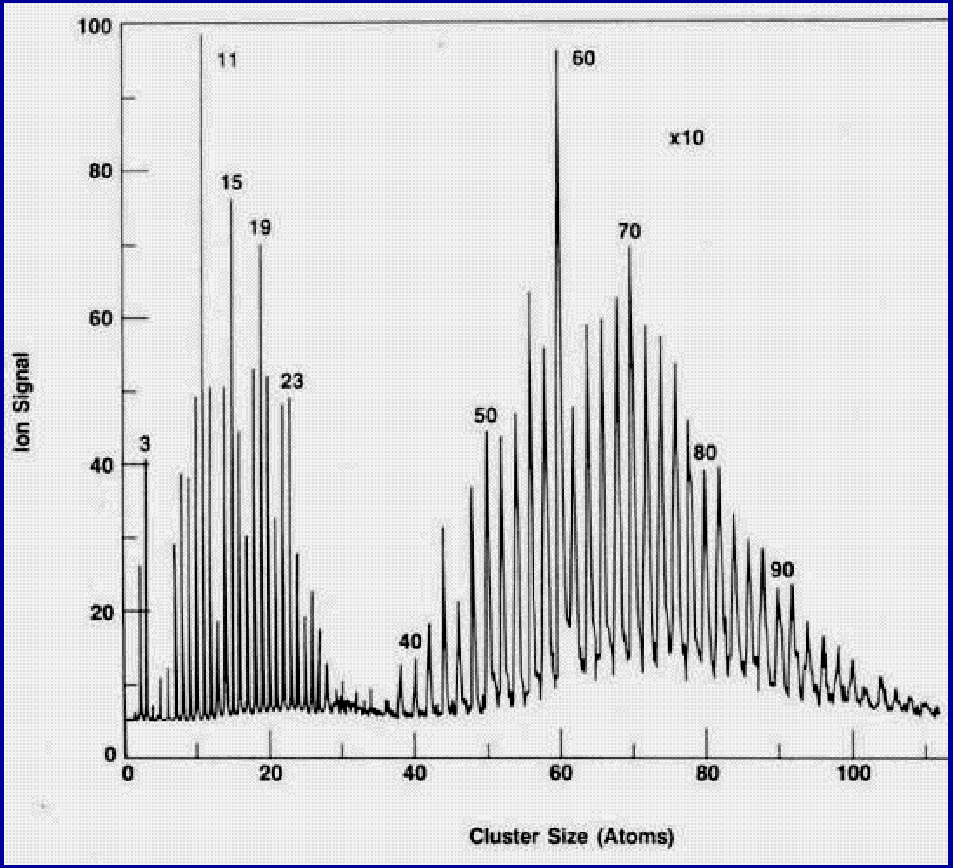




E. Osawa. *Kagaku (Kyoto)*, 25 (1970) 854 [in Japanese].



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



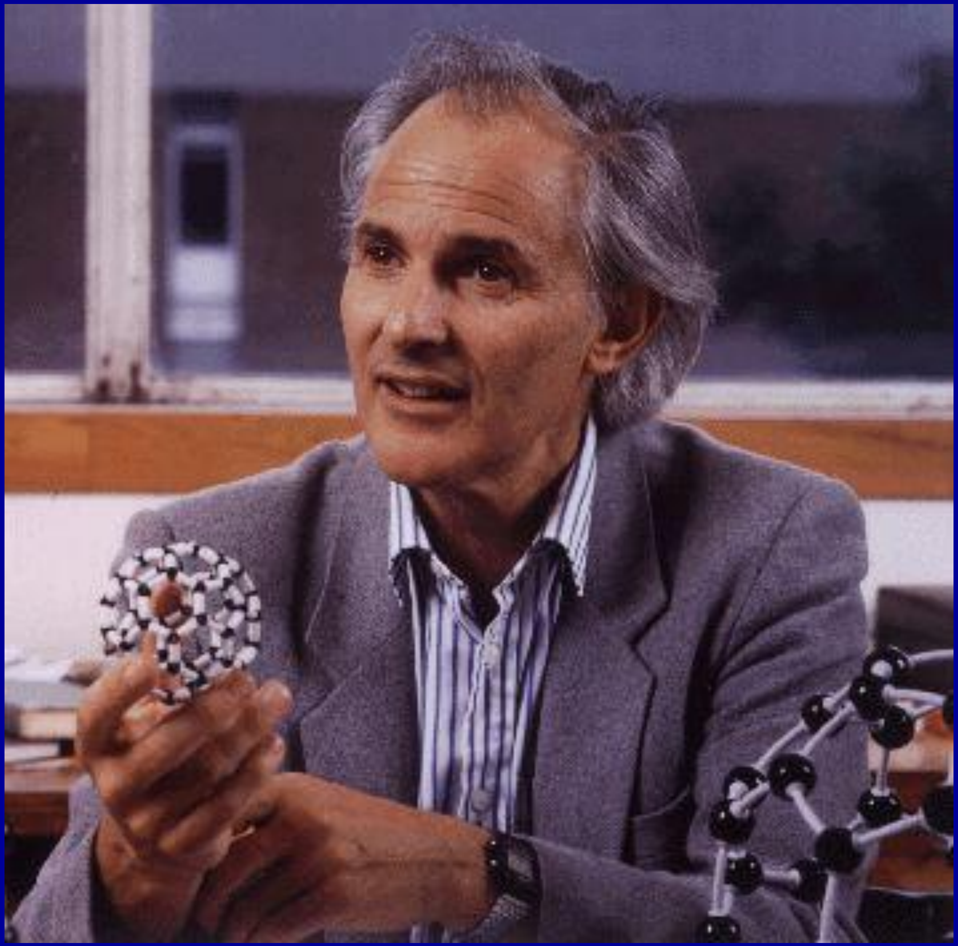
E.A. Rohlfing, D.M. Cox, A. Kaldor, J. Chem. Phys. 81, 3322 (1984).

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";

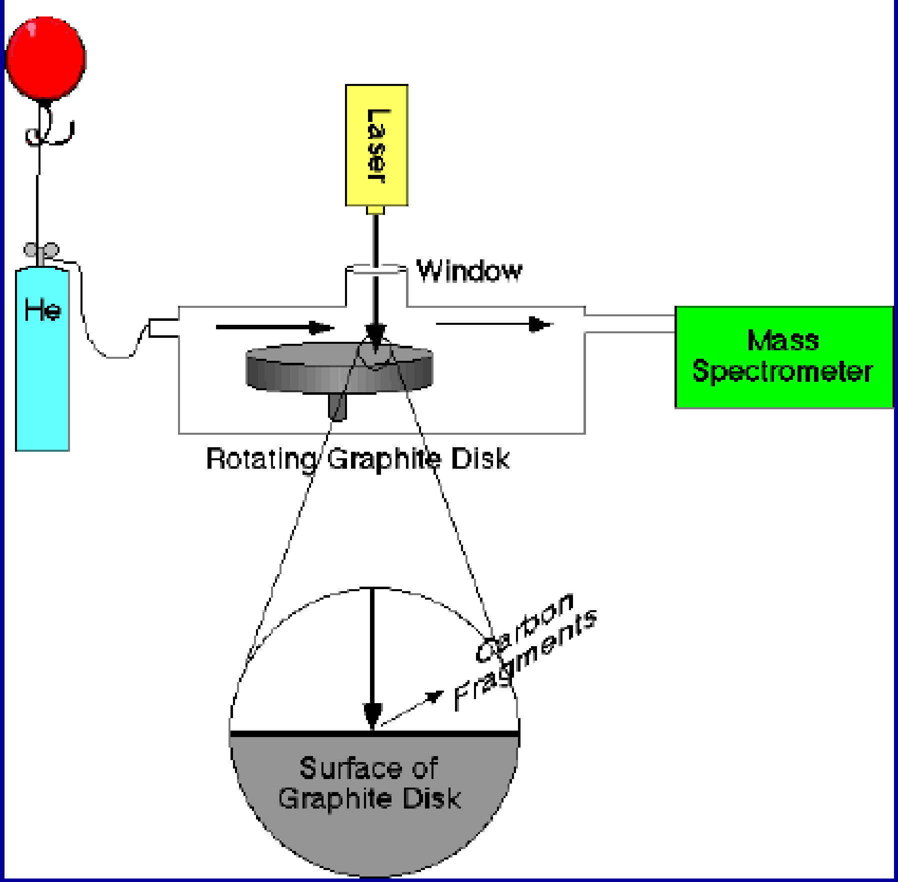
(3) 36 < n < 150 – even-numbered clusters (fullerenes)



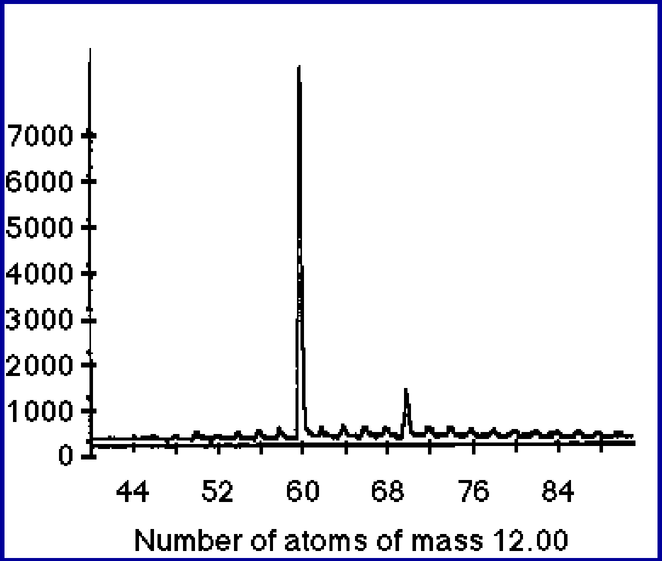
Harold Kroto

Richard E. Smalley (1943-2005)

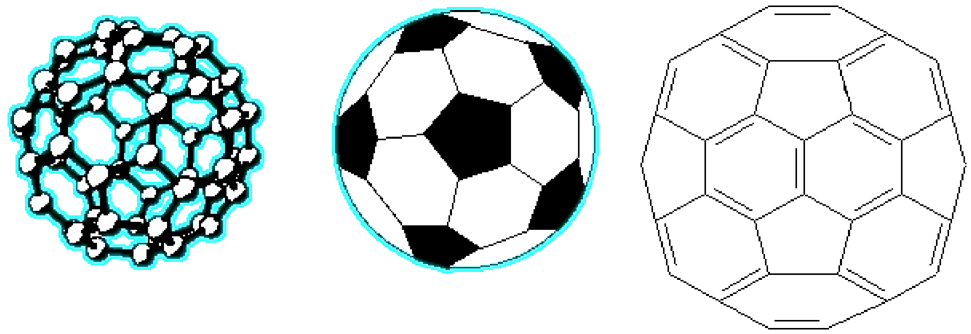
Jerusalem, 1995



September 1985, Rice University



Structure of C_{60}



Truncated icosahedron

12 pentagons;

20 hexagons

D = 7.1 Å

Single bond – 1.45 Å;

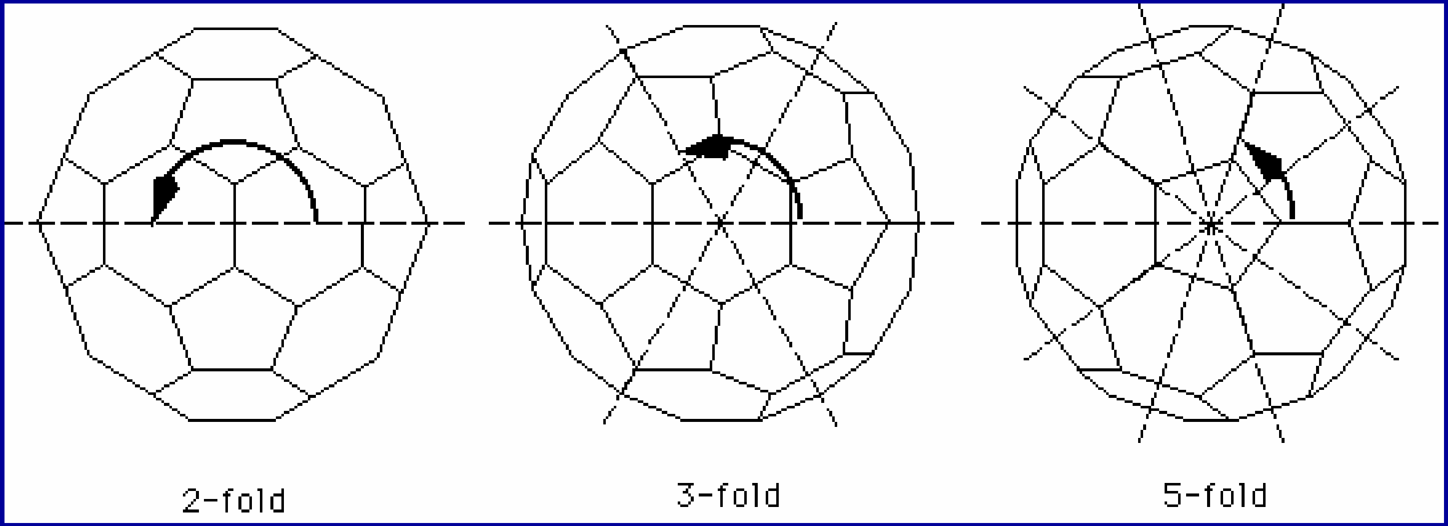
Double bond – 1.40 Å

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

Kroto, Curl and Smally – Nobel Price in chemistry, 1996

“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

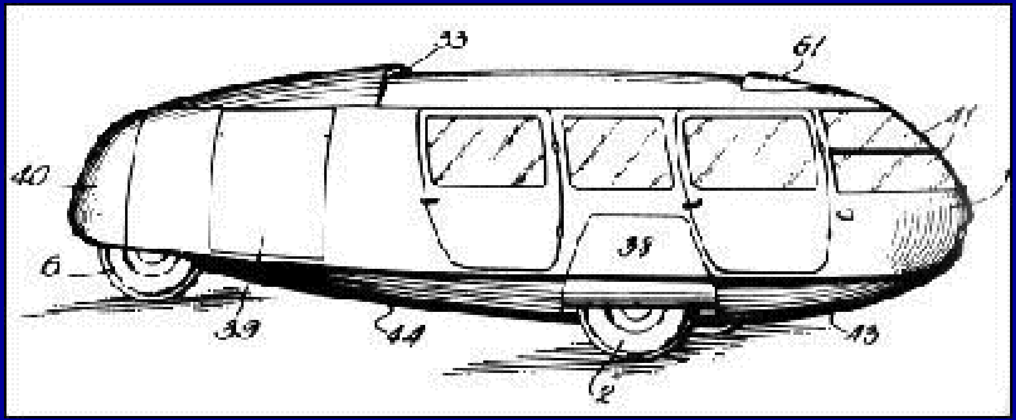
Richard Buckminster Fuller (1895-1983) –

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

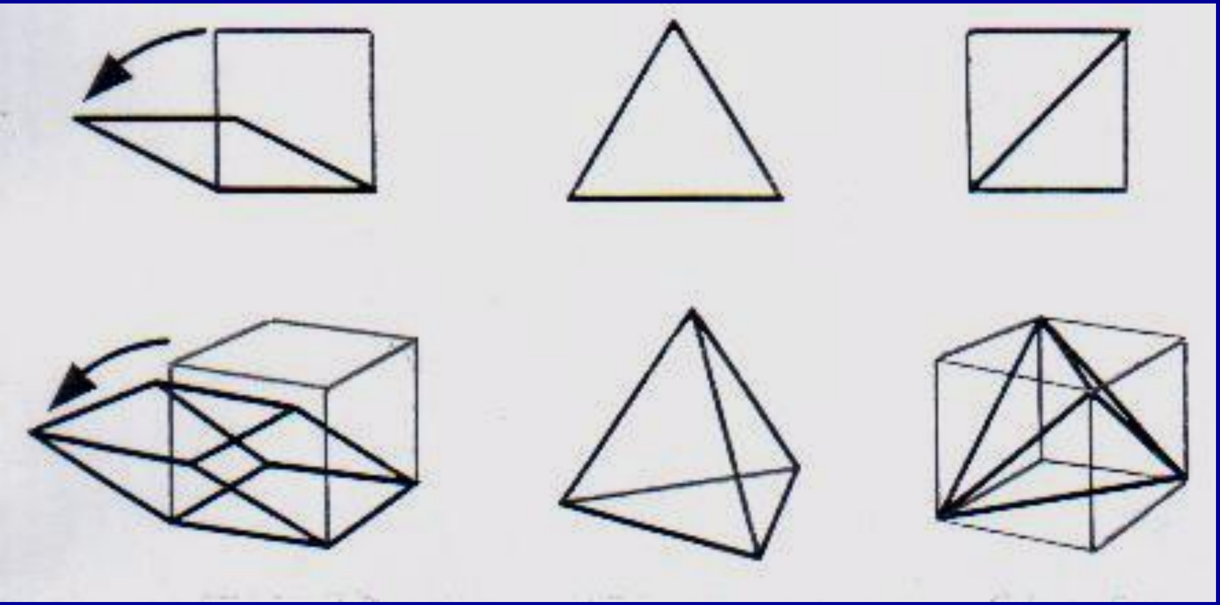
Dymaxion House, 1928.Wichita, Texas

Dymaxion Car, 1928-1933



190 km/hour, 12 passengers

Energetic-Synergetic Geometry

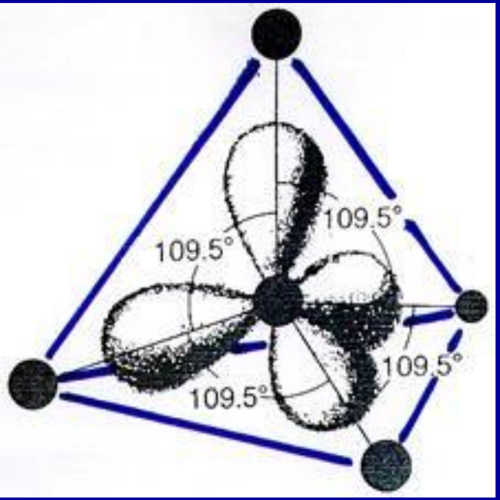


A
Unstable shapes
Square and
Cube

B
Stable shapes
Triangle and
Tetrahedron

C
Stable shapes
support
the unstable ones

Tetrahedral configuration of carbon bonds
Jacobus H. van't Hoff, 1874
First Nobel Price in Chemistry, 1901

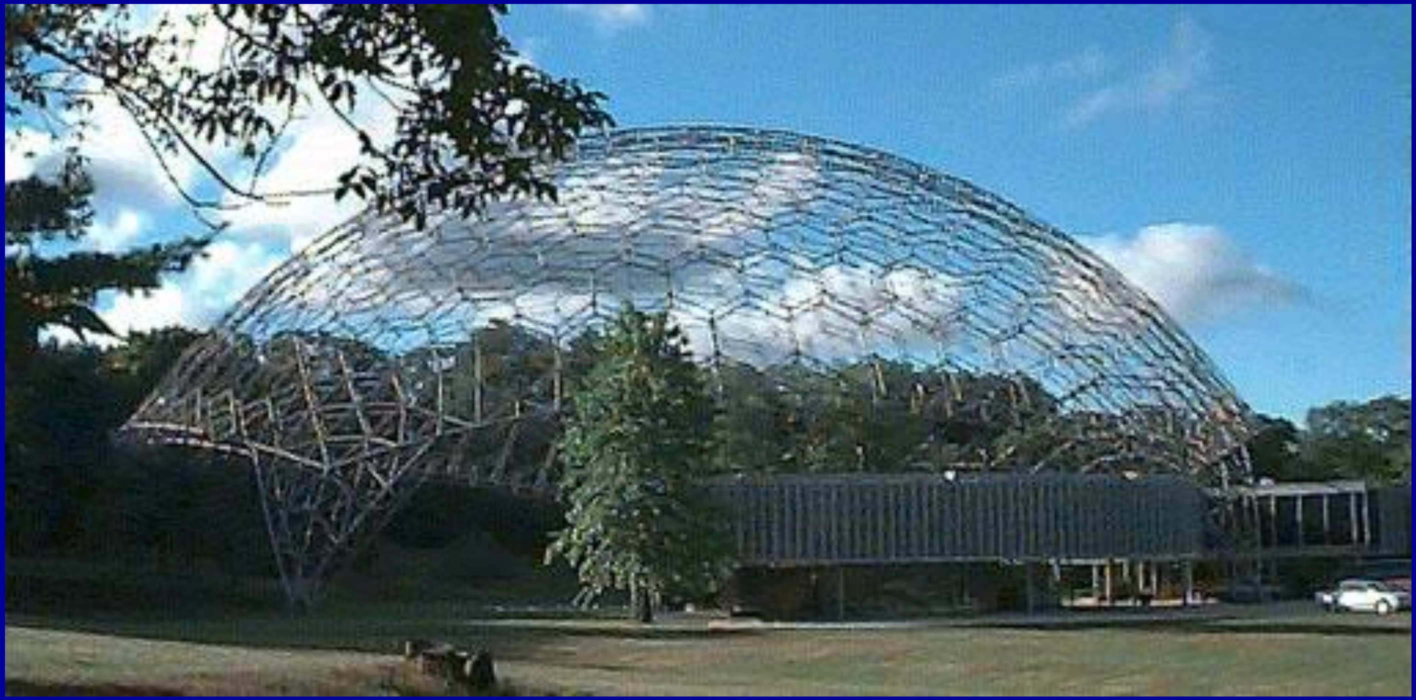


Square and cube (A) have no inherent structural strength – they can collapse in any direction. The triangle and tetrahedron (B) have built-in strength and stability. Column (C) shows how square and cubes become stable *only* when turned into triangles and tetrahedra.

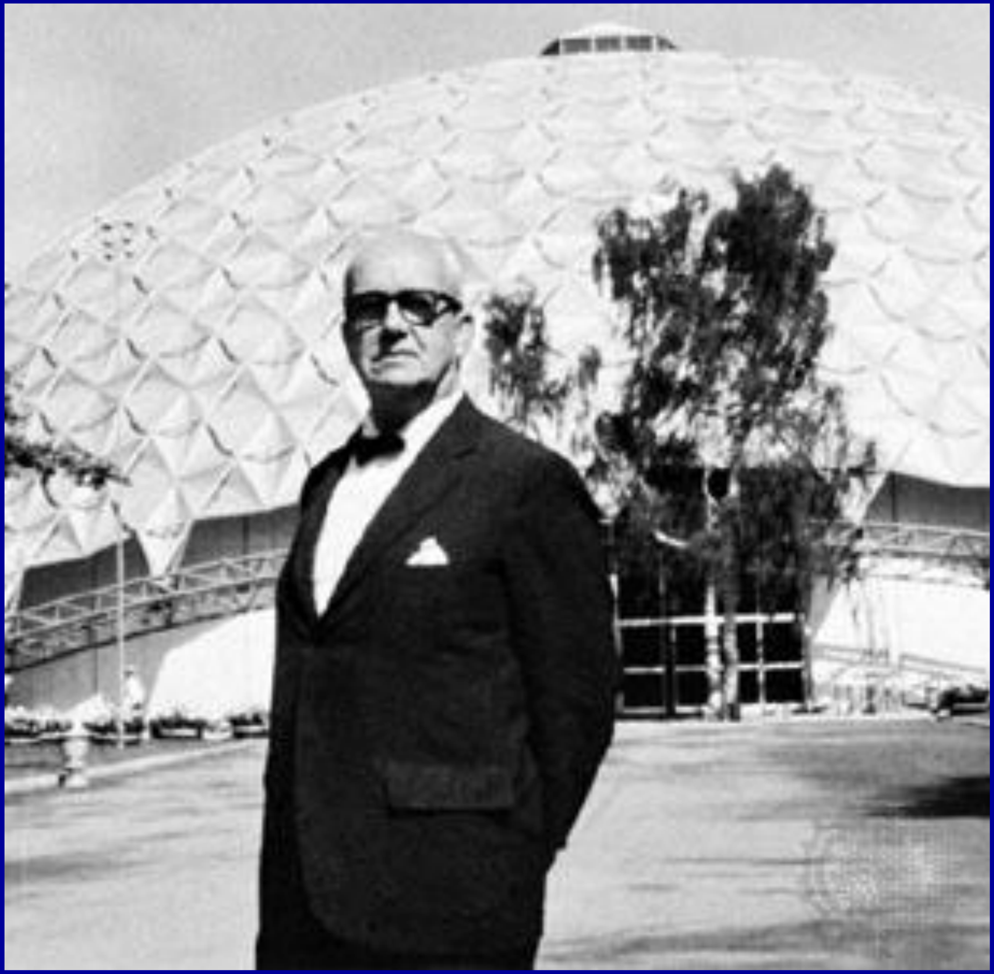
1954 - the first Bucky's patent on geodesic domes;

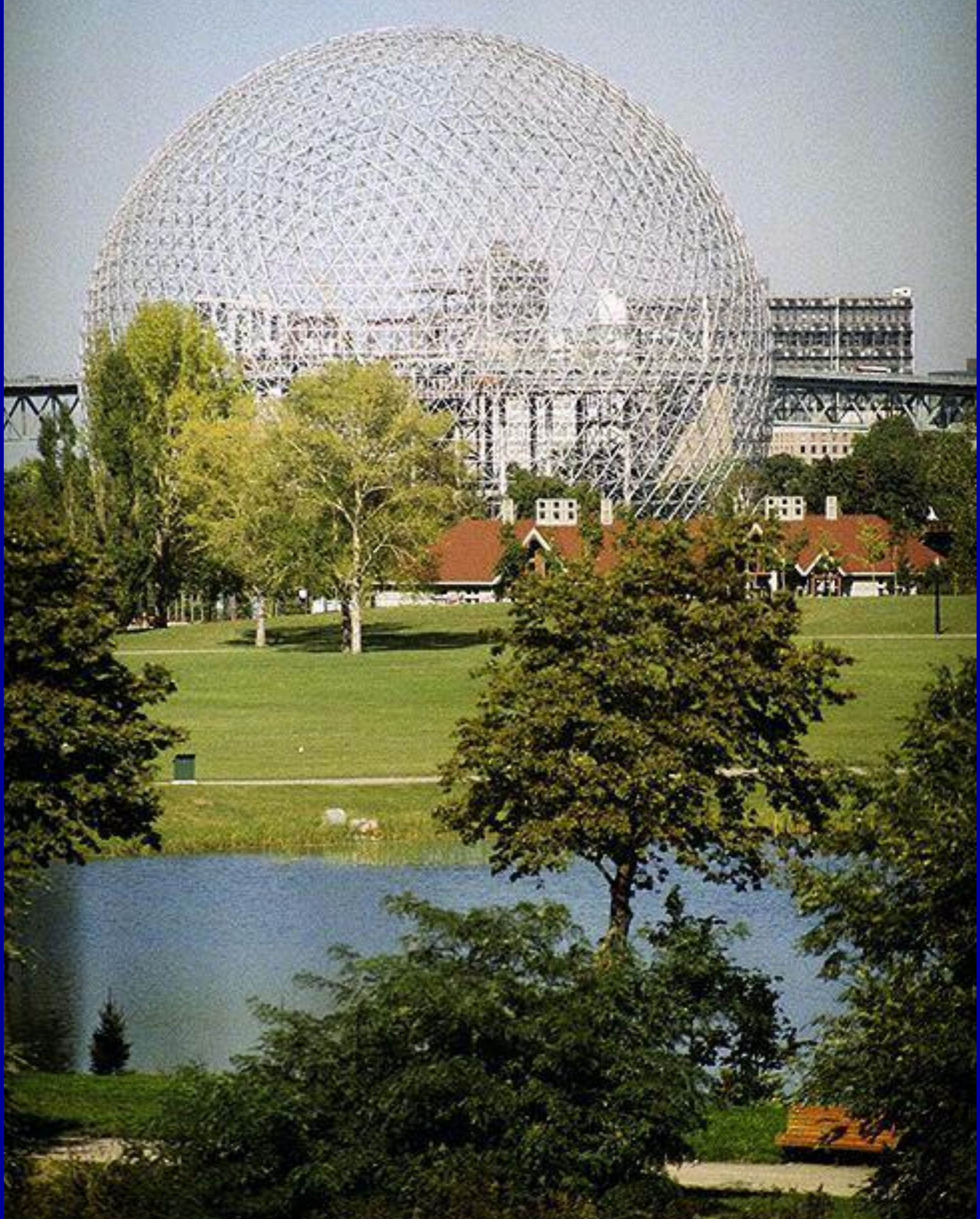
1958 - geodesic dome for the Union Tank Car Company (Los Angeles), 117 m diameter and 35 m height;

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)

<u>Geodesic sphere</u> **is a polyhedral structure could be effectively inscribed in a sphere.**

<u>Geodesic domes</u> **are fractional parts of complete g*eodesic spheres*. Actual structures range from less than 5% to 100% (a full sphere).**

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.

GEOD, Paris. Photo by E. Katz

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

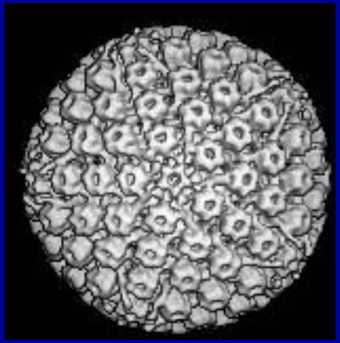
Frequency **of a dome relates to the number of smaller triangles into which it is subdivided. A high frequency dome has more triangular components and is more smoothly curved and sphere-like**

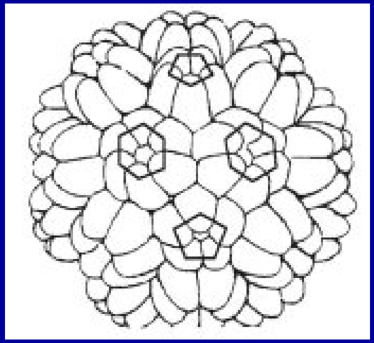
Geodesic domes get stronger, lighter and cheaper per unit of volume as their frequency and size increase - just the opposite of conventional building

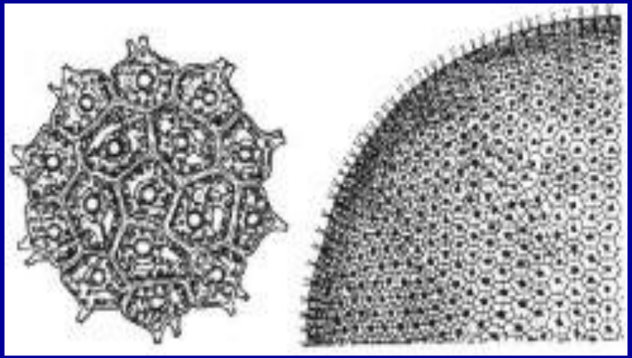
'Garden of Eden', Cornwall, UK, 2001

Photo by E. Katz

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

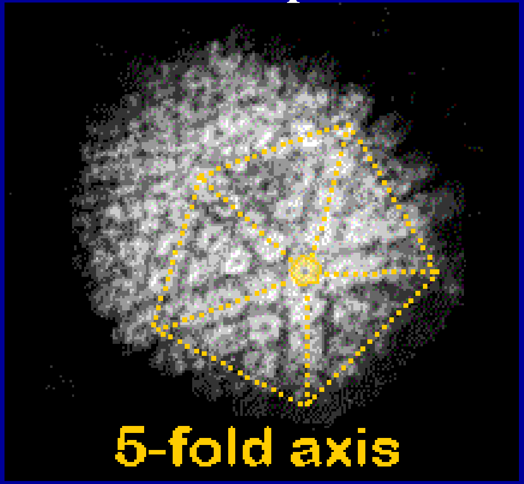






20-300 nm

Herpes

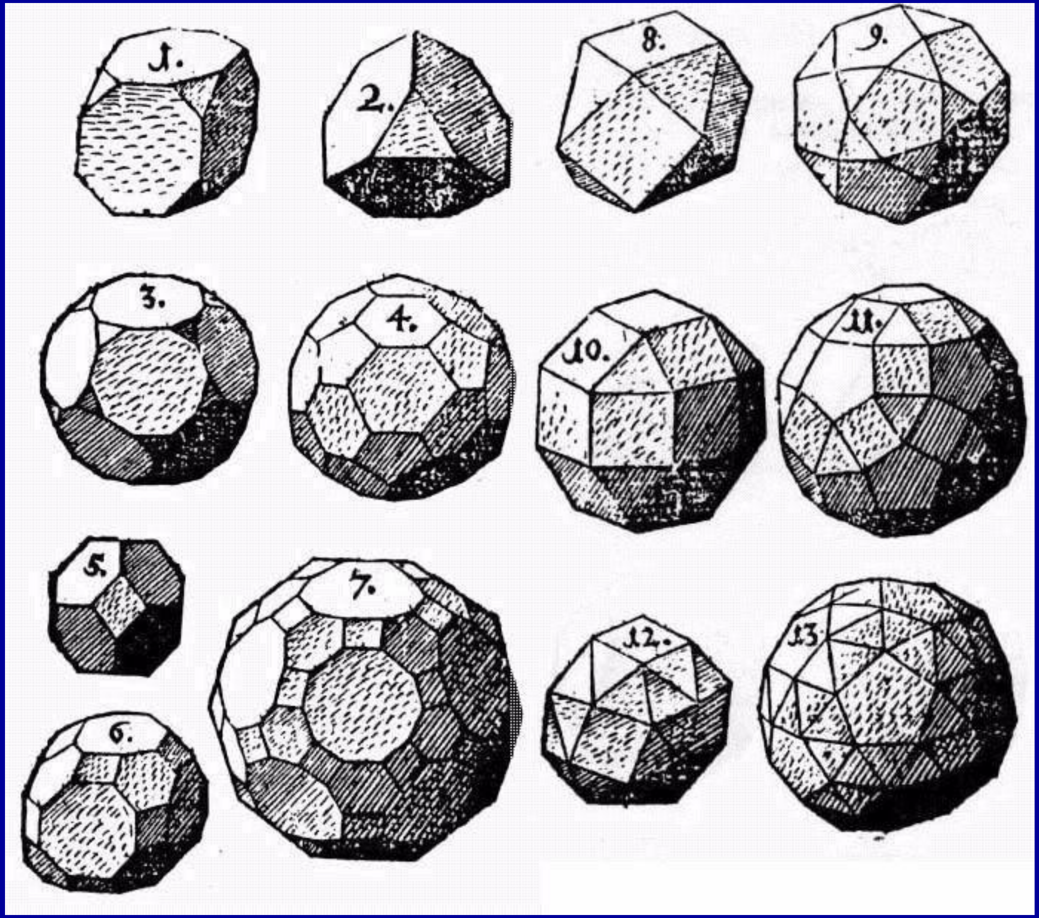


D.L.D. Caspar and A. Klug. Physical Principles in the Construction of Regular Viruses, in Cold Spring Harbor Symp. Quant. Biol. V.27, 1 (1962):

"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."

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

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



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 polyhedra* or *platonic solids)*

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

1619

Platonic solids (regular polyhedra)

Classical elements:

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

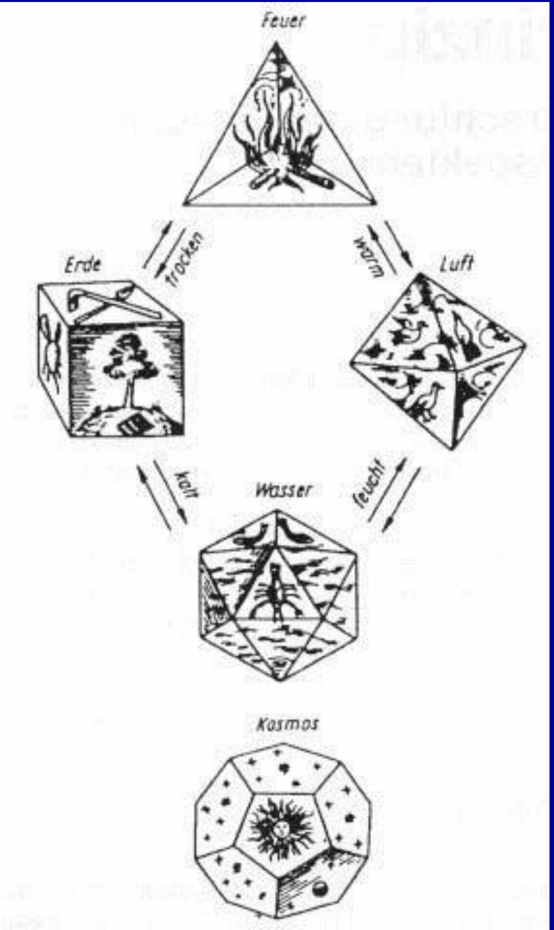
Tetrahedron - fire,

Cube - earth,

Octahedron - air,

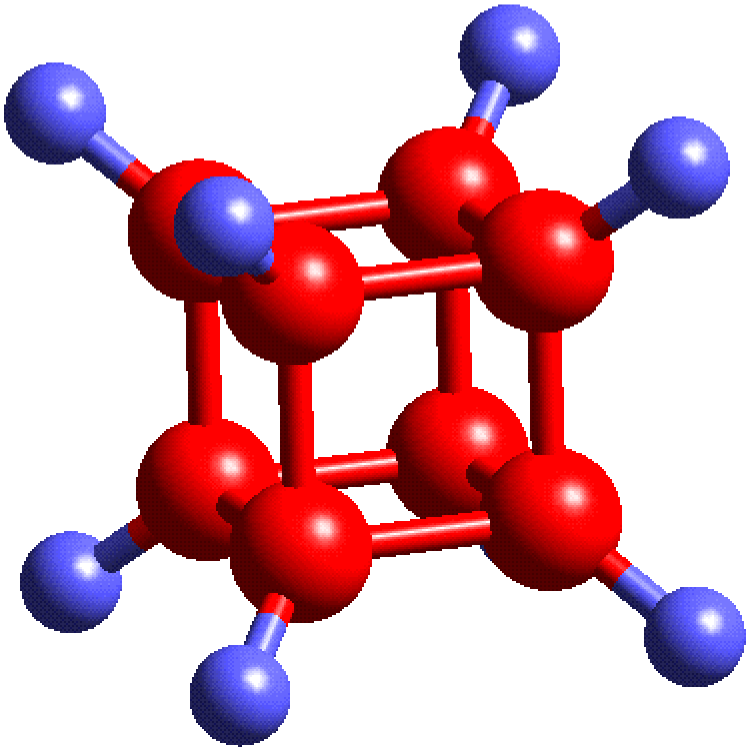
Icosahedron - water,

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



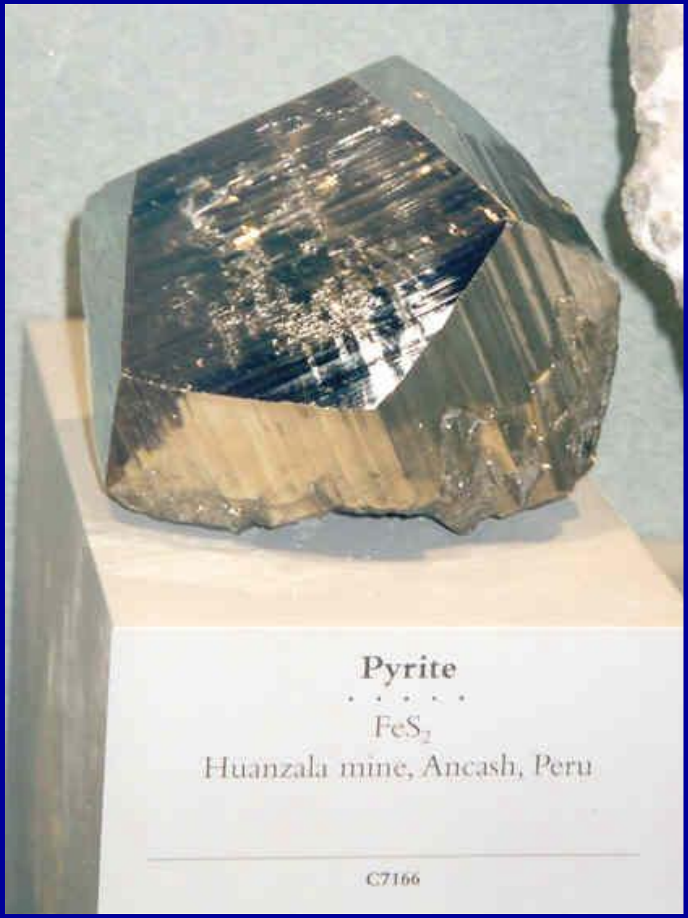
From Johannes Kepler's "Harmonice Mundi" ("The Harmony of the World"), 1619

“Forbidden” chemical compound – **Cubane – C_8H_8** (1964)

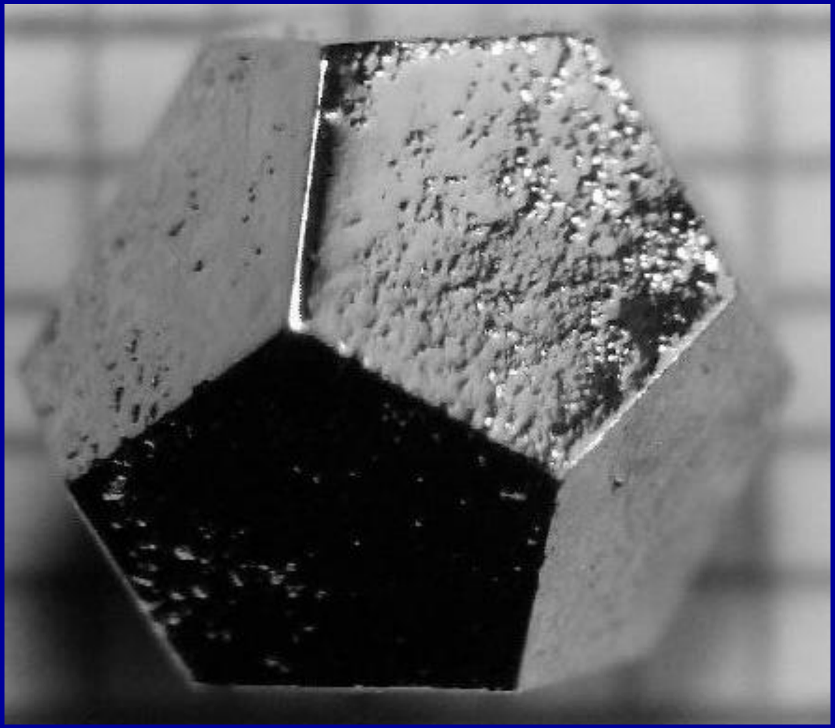


Quasi-Octahedron. Louvre, Paris.
Photo by E. Katz

Dodecahedron



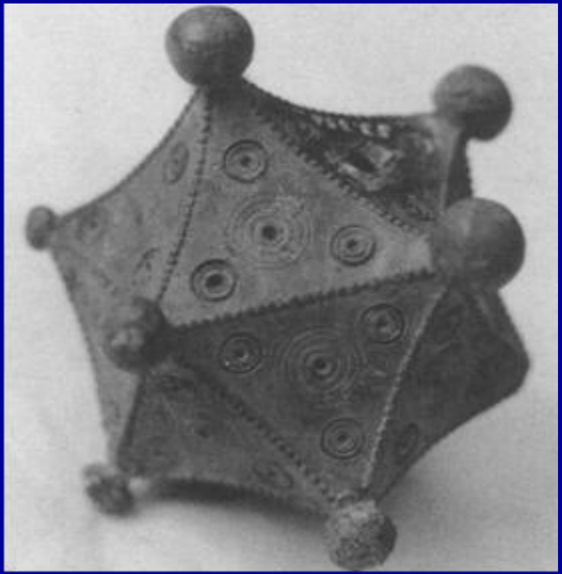
Natural History Museum,
Washington, D. C.
Photo by E. Katz



Quasicrystal of a Ho-Mg-Zn alloy.

Photo from Wikipedia.

Sundial by John Mylne (1633). Courtyard of the Palace of Holyroodhouse, Edinburgh. Photo by E. Katz

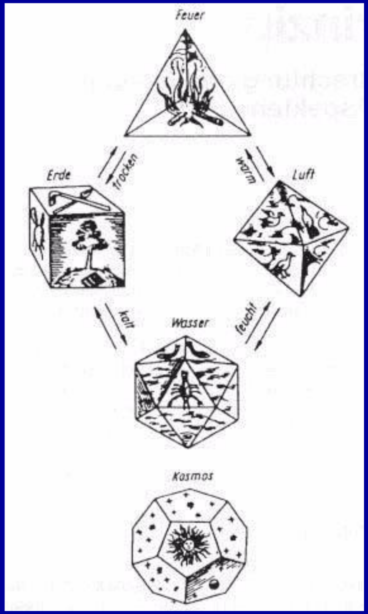


Bronze icosahedron (about 100-300 A. D.) excavated in the Roman provinces along the Rhine river. Photo from [B. Artmann, The American Mathematical Monthly, 18, 132 (1996)].

Nicolas Dings. Monument to Baruch de Spinoza (2008). Amsterdam. Photo by E. Katz

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

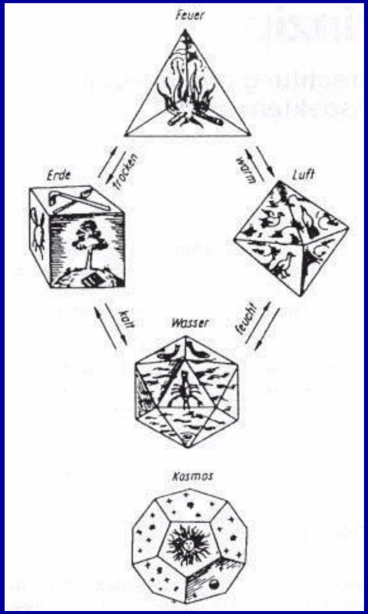


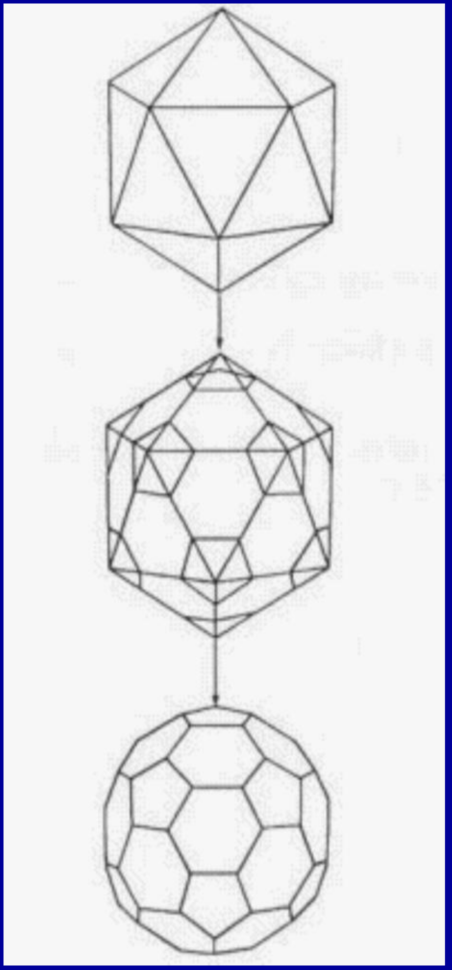
Duality:

Cube and *octahedron* are dual to each other; icosahedron is dual to dodecahedron (and vice versa) and tetrahedron is dual to itself.

Characteristics of platonic solids

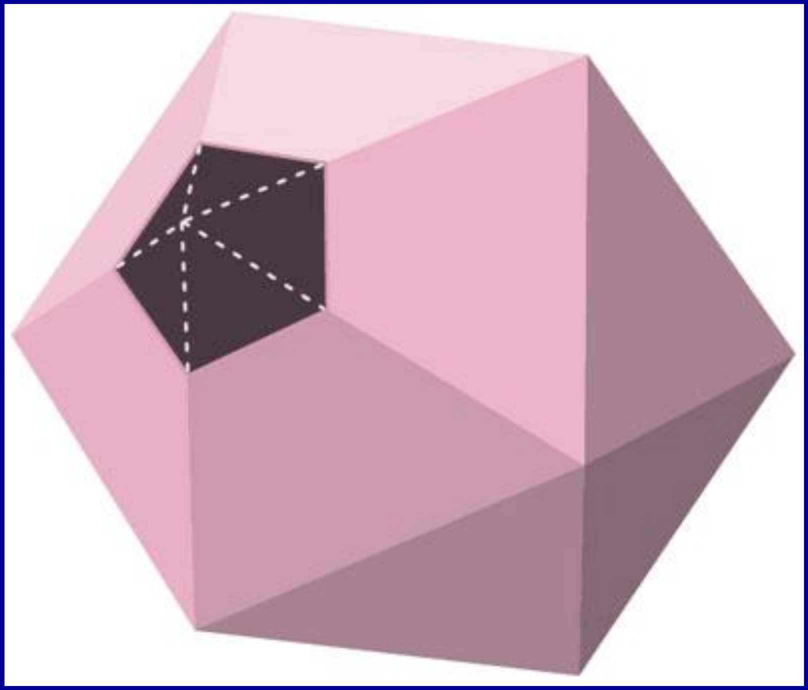
Polyhedron	Edges in each face, *m*	Edges that connect in each vertice, *n*	Faces, F	Edges, E	Vertices, V	F-E+V
Tetrahedron	3	3	4	6	4	2
Cube	4	3	6	12	8	2
Octahedron	3	4	8	12	6	2
Icosahedron	3	5	20	30	12	2
Dodecahedron	5	3	12	30	20	2

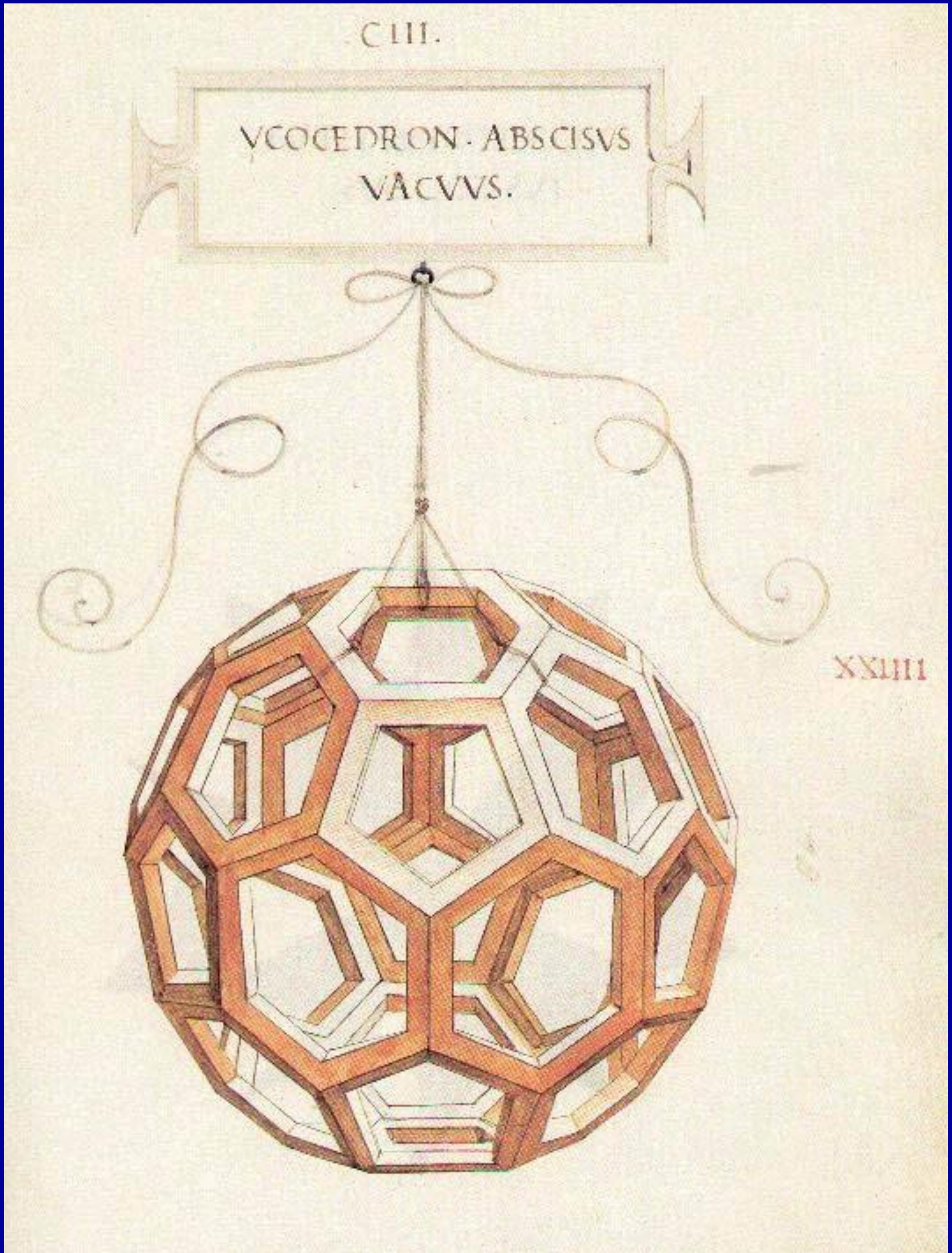




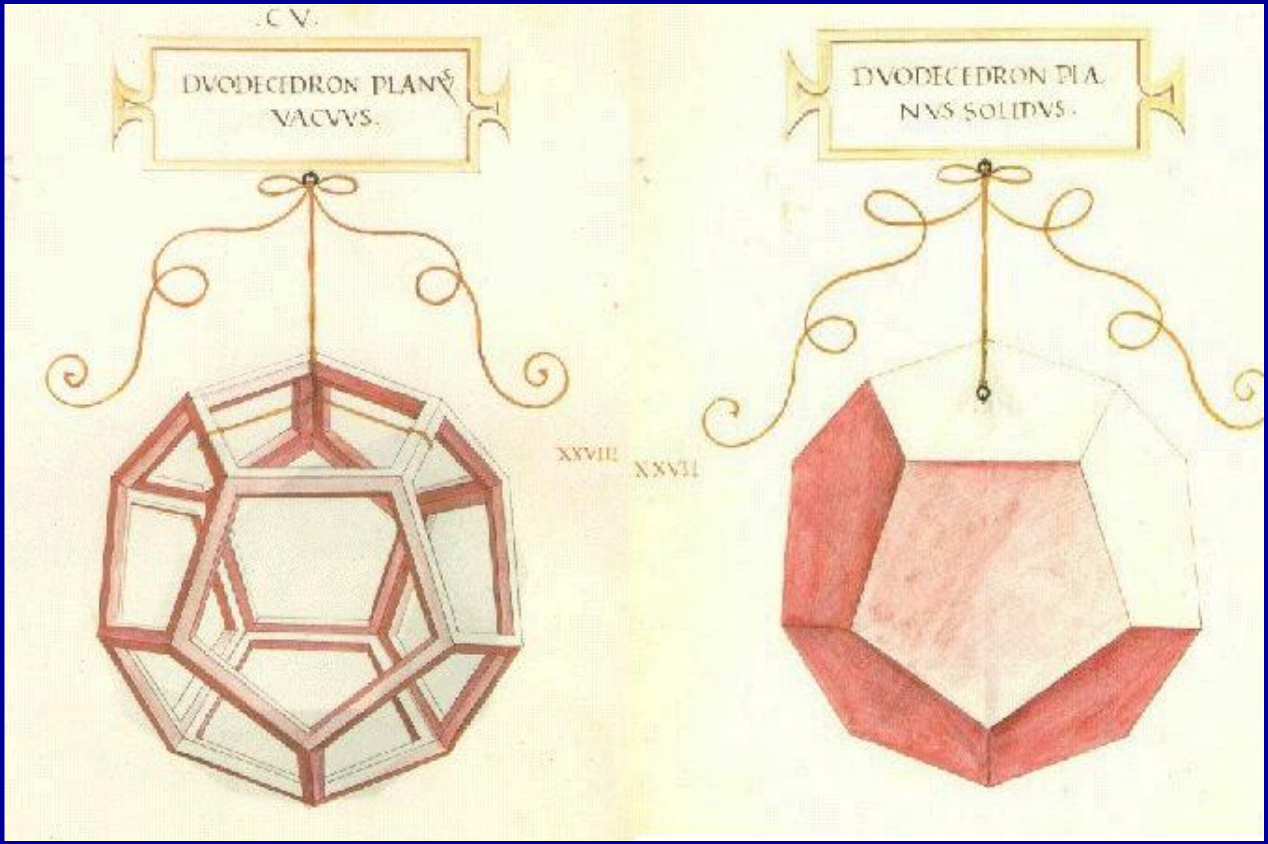
https://www.americanscientist.org/article/the-topology-and-combinatorics-of-soccer-balls?fbclid=IwY2xjawFp-DNleHRuA2FlbQIxMQABHa0zUKxl-HwHlhFeivM-gI8IHrEcKv5Mz6bUDGdIreciug9PaqcRsMhp4Q_aem_FQWyq48fQpw2zn3qdWgDqw

American Scientist
The Topology and Combinatorics of Soccer Balls
By Dieter Kotschick

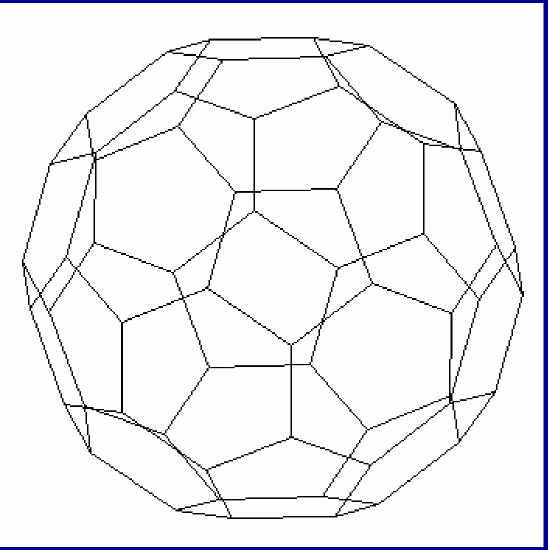




Leonardo’s drawing of truncated icosahedron from Luca Pacioli’s book “The Devine Proportion” (“De Devina Proportione”), 1509



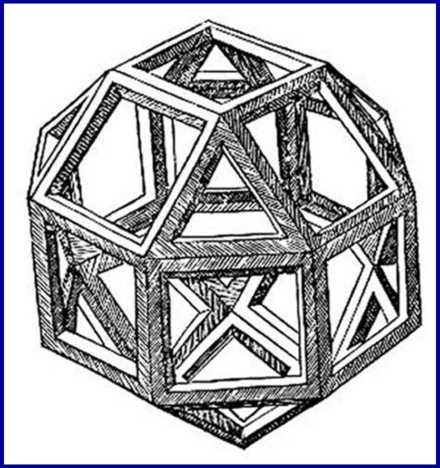
Leonardo's drawing of dodecahedron by a method of *solid segments* and *solid faces* from Luka Pacioli's book "The Devine Proportion" ("De Devina Proportione"), 1509



Luca Pacioli, 1445-1517

Rombicuboctahedron

Jacopo de Barbari. Luca Paciolli's portrait, 1495



Rhombicuboctahedron.
(a) Leonardo’s printing in “The Devine Proportion” (1509). (b) National Library of Republic of Belarus in Minsk (2006, architects Mihail Vinogradov and Viktor Kramarenko). Photo by Galya Katz.

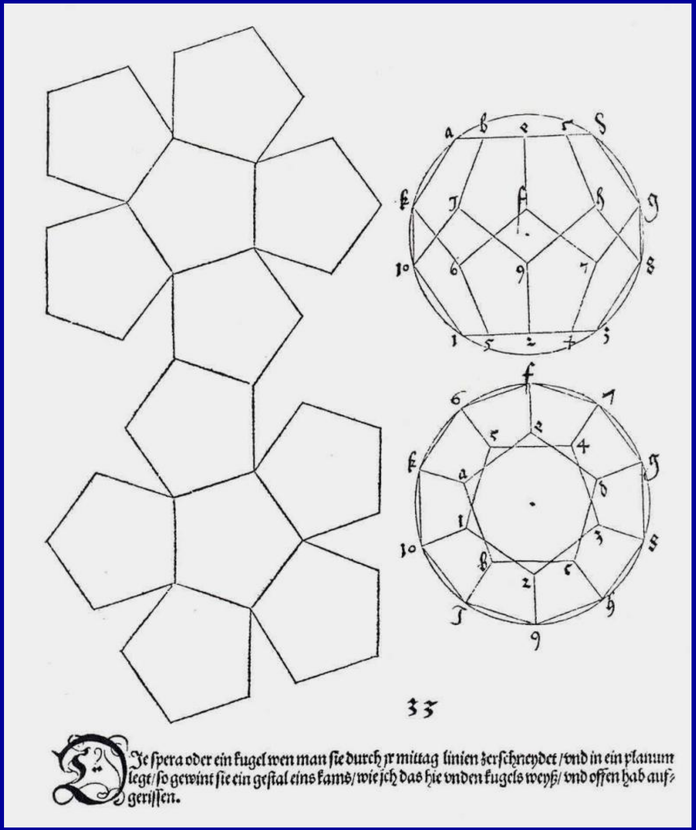
Luca Pacioli, 1445-1517

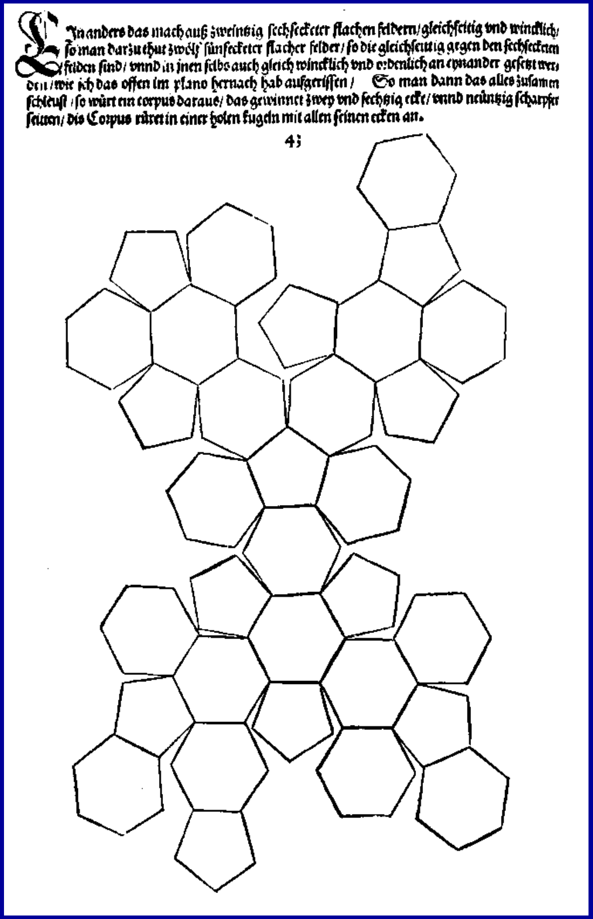
Rombicuboctahedron

Jacopo de Barbari. Luka Paciolli’s portrait, 1495

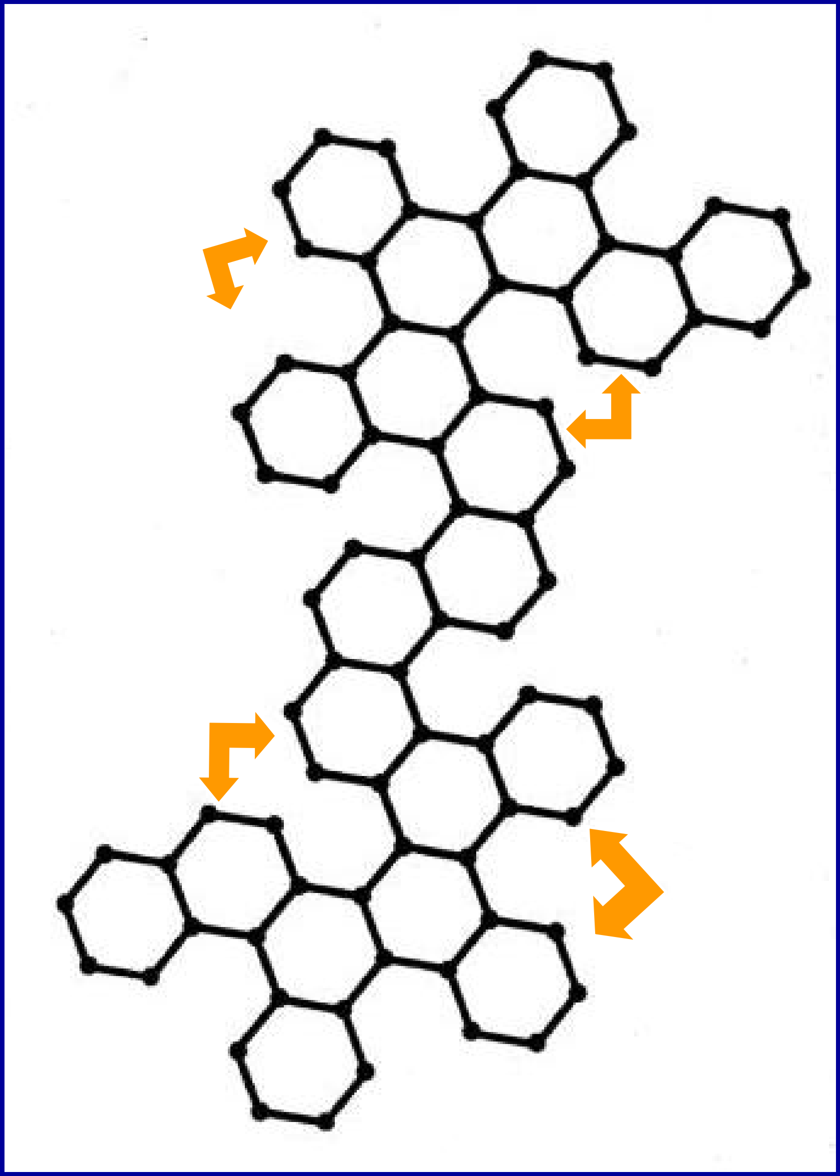
Albrecht Durer, 1471-1528

Self-portrait, 1498





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;

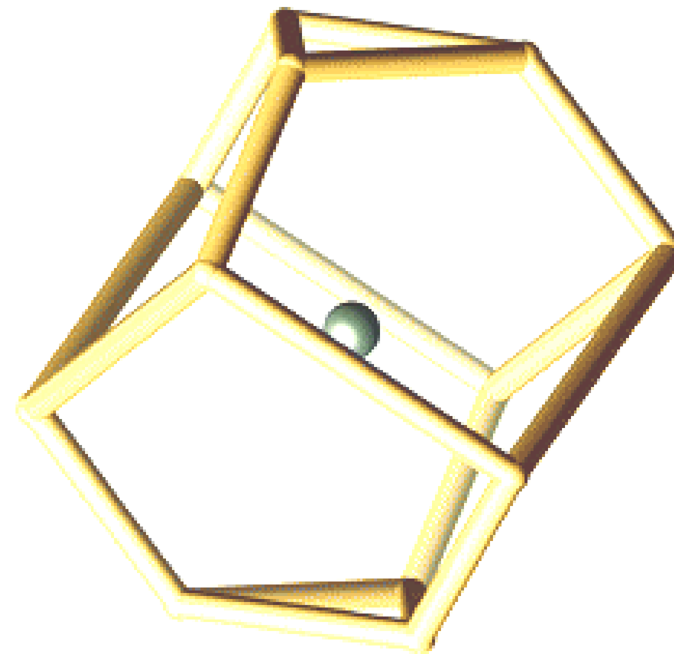
- Carefully cut it; -

-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.

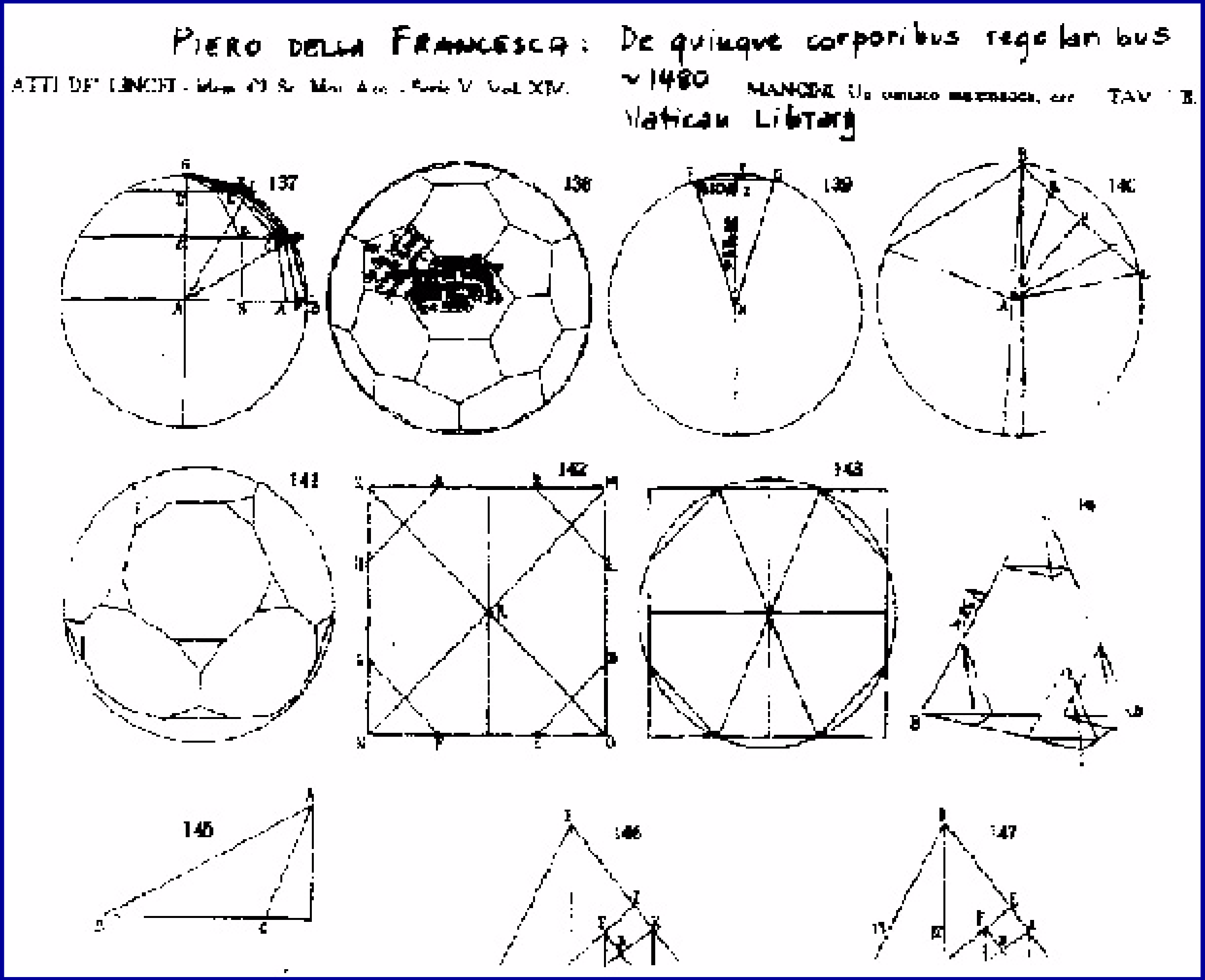
Truncated rhombohedron (Dürer's solid)

Albrecht Dürer. “Melancholia I ” (1514)



$NiAs_{12}$ cluster

Piero della Francesca (1420 - 1492)



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

Piero della Francesca. *Montefeltro Altarpiece,* 1465, Pinacoteca di Brera, Milan

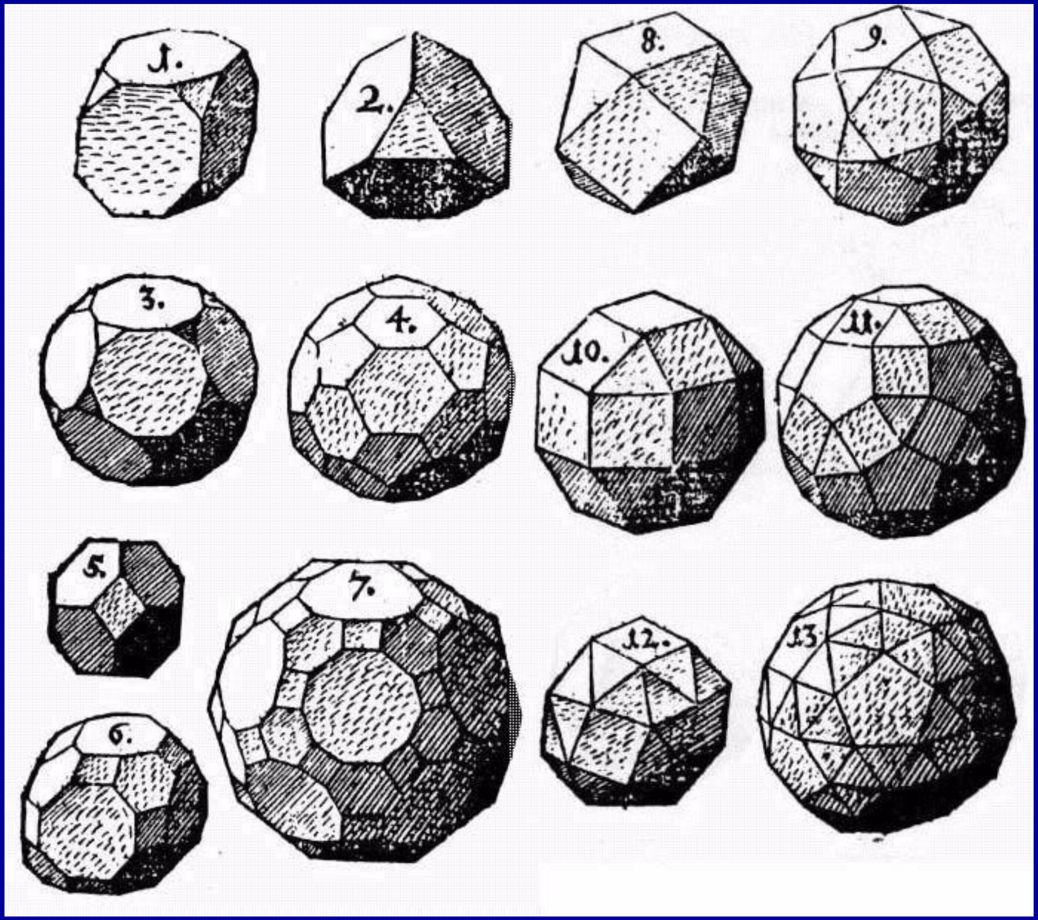
Memorial desks of Piero della Francesca and Luca Pacioli in San Sepolcro.

Photos by E. Katz

In honor of Piero della Francesca
in the fifteenth century
the sovereign painter
from whose mastery Perugino
learned the marvels of art
and Italy the geometric principles of perspective
here where her great son lived
and where at 82 years he ascended into the heavens
this memorial is placed in the year 1876
by a grateful and reverential country

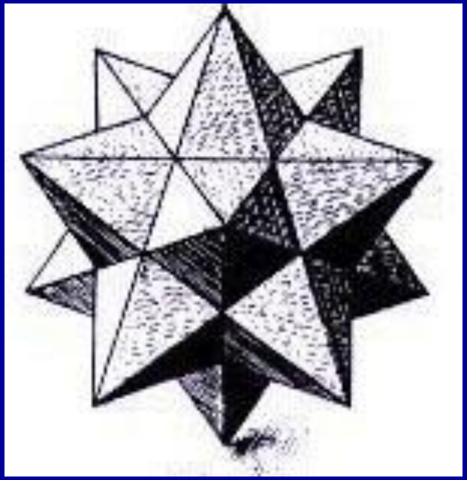
To Luca Pacioli who was friend and consultant
to Leonardo da Vinci
and Leon Battista Alberti
who first gave to algebra the language
and the structure of science
and whose was the great discovery
of applying it to geometry…
The people of San Sepollcro upon
the initiative of the society of workers
ashamed of 320 years of oblivion
to the great fellow citizen
placed [this memorial] in 1878

Archimedian polyhedra or archimedean solids



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

Star-like regular polyhedra

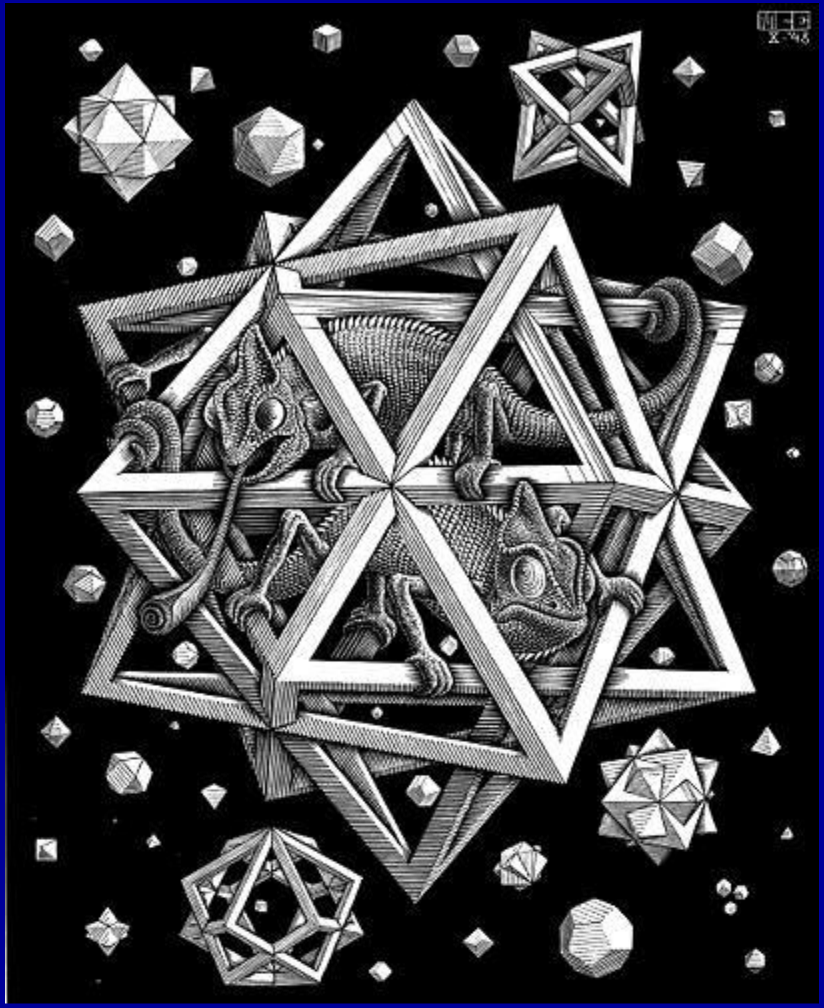


Johannes Kepler.
"Harmonice Mundi"
("The Harmony of the World"),

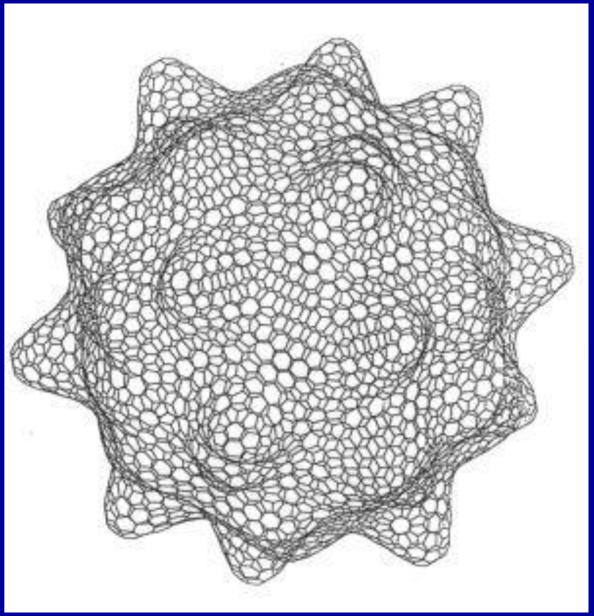
1619

Paolo Ucello (~ 1420's ?). St Marco Cathedral, Detail of mosaics

Monument by Mimmo Paladino near to the entrance to Leonardo da Vinci Museum in the village of Vinci (Leonardo's birthplace, Toscany). Photo by E.A. Katz.



M.C. Escher. Stars (1948)



Star-like carbon cluster

Intarsia panels by Fra Giovanni da Verona (1457 - 1525) in Territorial Abbey of Monte Oliveto Maggiore (near Siena)

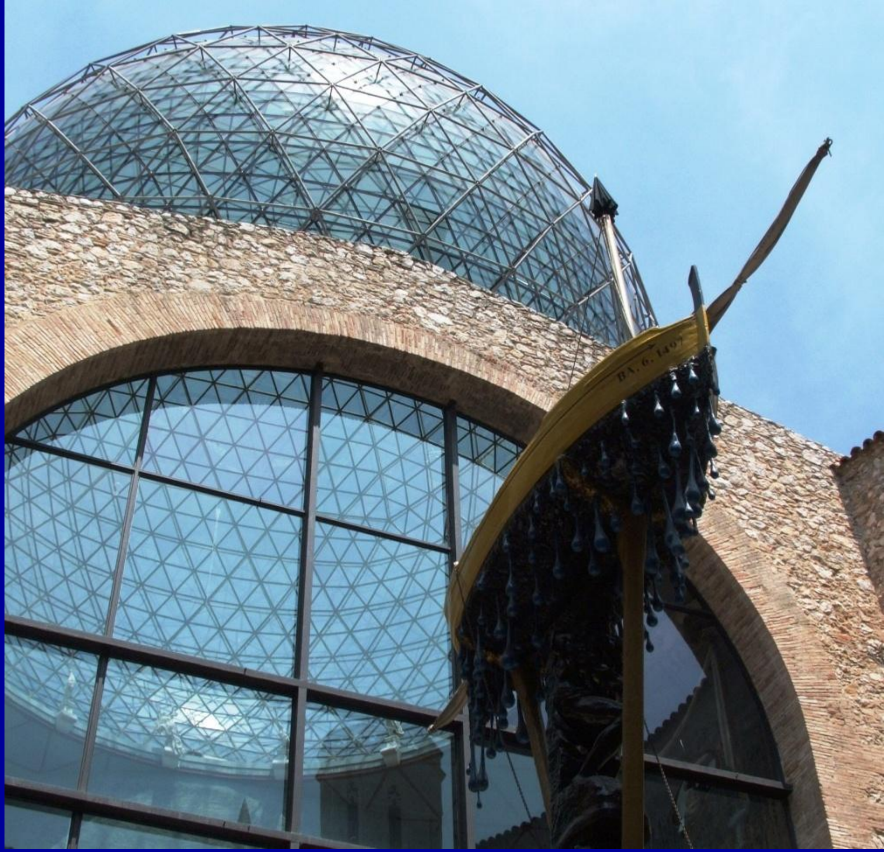
Photo by E. Katz

Salvador Dali. “The Sacrament of the Last Supper (1955). The National Gallery of Art in Washington, D.C.

Salvador Dali. “In search of the fourth dimension” (1979).
Fundació Gala-Salvador Dalí, Figueres.

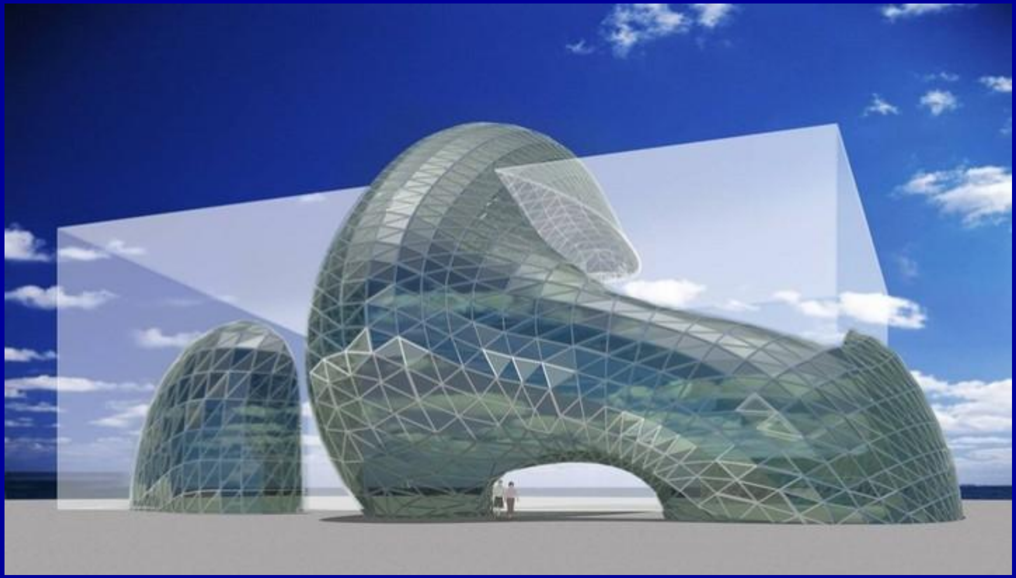
Photo by
E. Katz

Dalí House-Museum ,Port Lligat,
Spain



Dalí Theatre –Museum, Figueres, Spain
[arch. Emilio Pérez Piñero (1935-1972)]

Dali Museum, St. Petersburg, FL (architect Yann Weymouth, 2011)



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)

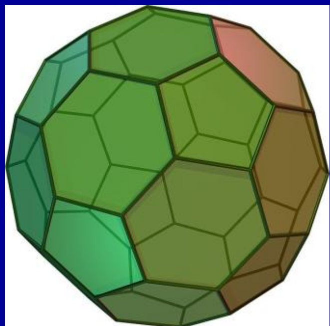
L. Euler, Novi corumentarii academie Petropolitanae 4, 109 (1752/3).

General Euler’s theorem

$$F - E + V = n$$

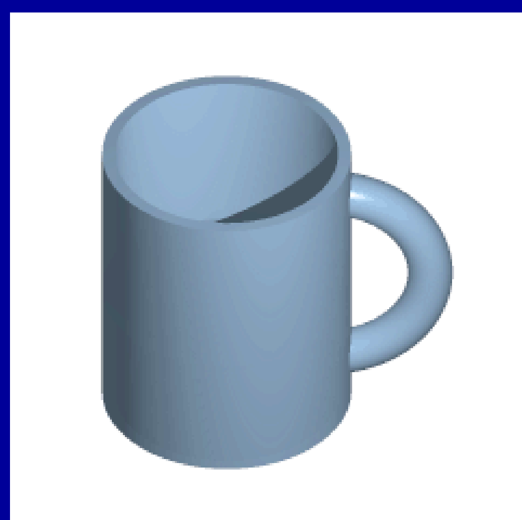
n – Euler’s parameter
(n = 0 for torus, n=2 - 2g for polyhedra with g ‘through holes’)

This is the first theorem of topology, part of mathematics that is concerned with the properties of a geometric object that are preserved under continuous deformations, such as stretching, twisting, crumpling and bending, but not tearing or gluing.



A convex polyhedron (truncated icosahedron) is homeomorphic to a sphere (soccer ball)

A continuous deformation (a type of *homeomorphism*) of a cow into a sphere and a cup into a torus



Henry Segerman. Topological joke. Topological transformations of surfaces with *genus* 1. The dumpling (torus) is constantly transformed into a cup (bullet with 1 handle).

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

$2E = 5p + 6h$

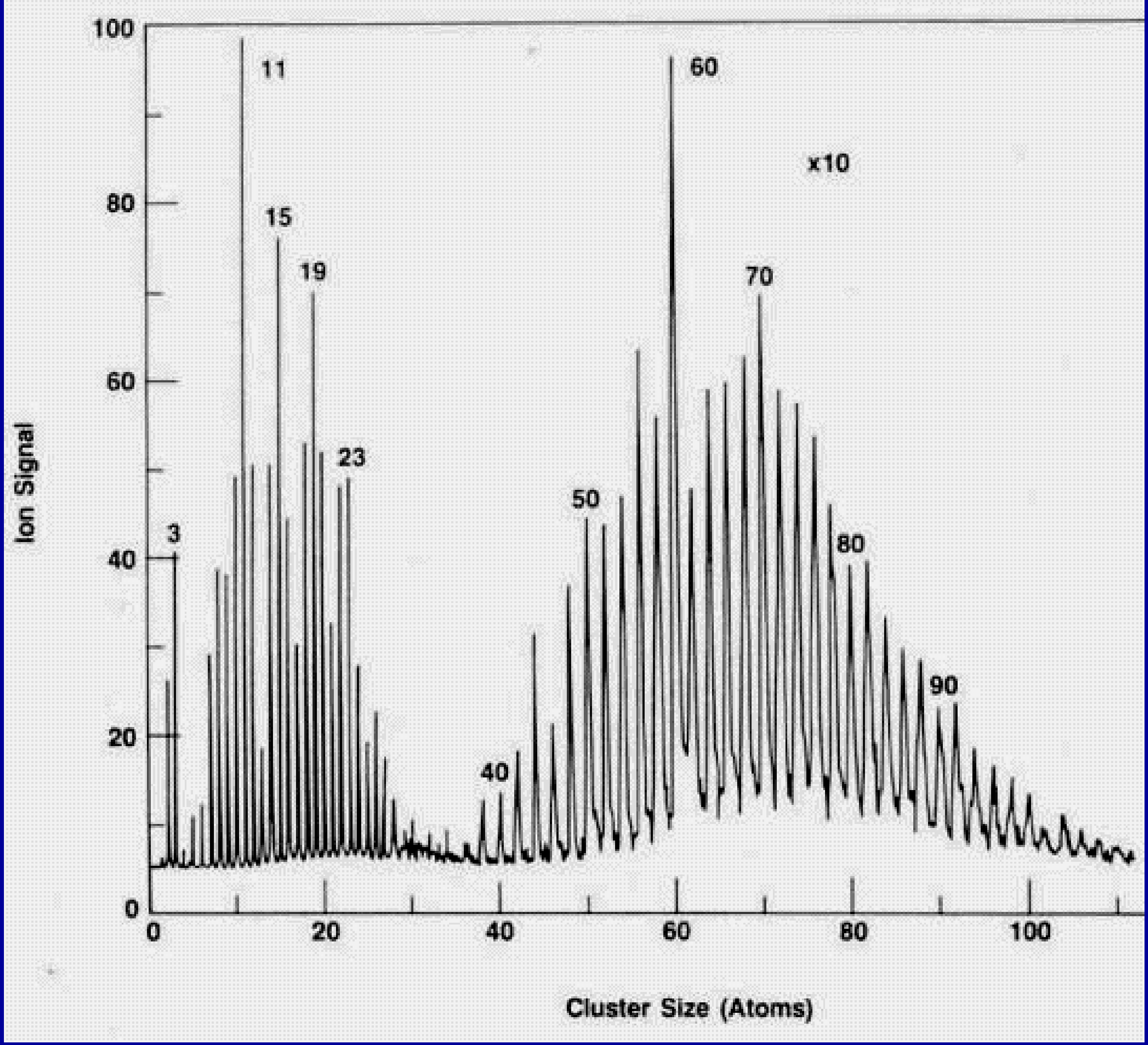
$3V = 5p + 6h$

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

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

$$p = 12$$

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



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

$$F – E + V = 2$$

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

$2E = 5p + 6h$

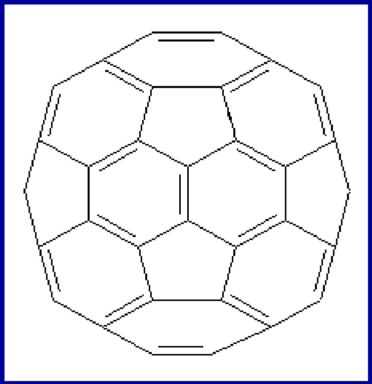
$3V = 5p + 6h$

$6(F – E + V) = p$

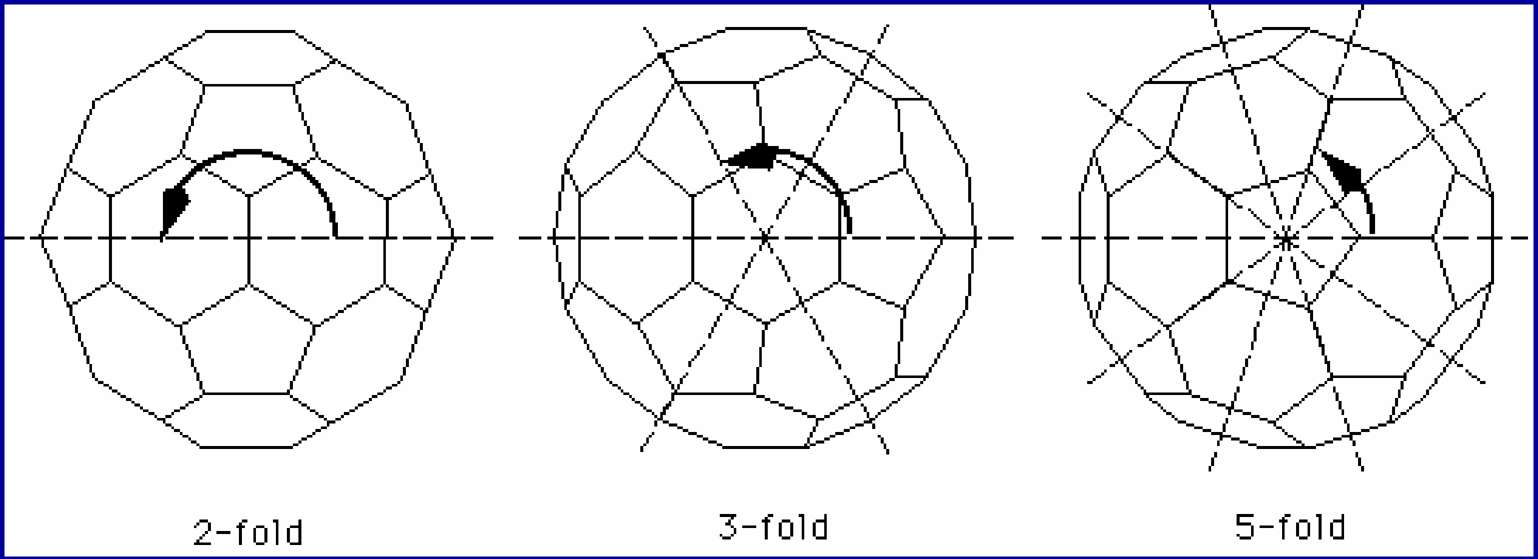
$$p = 12$$

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

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



Isolated pentagon rule



15 rotation axes

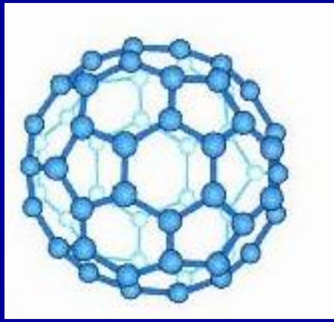
180°

10 rotation axes

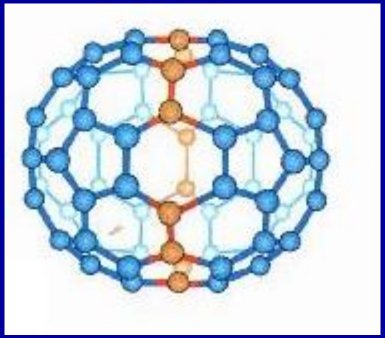
120°

6 rotation axes

360/5=72°

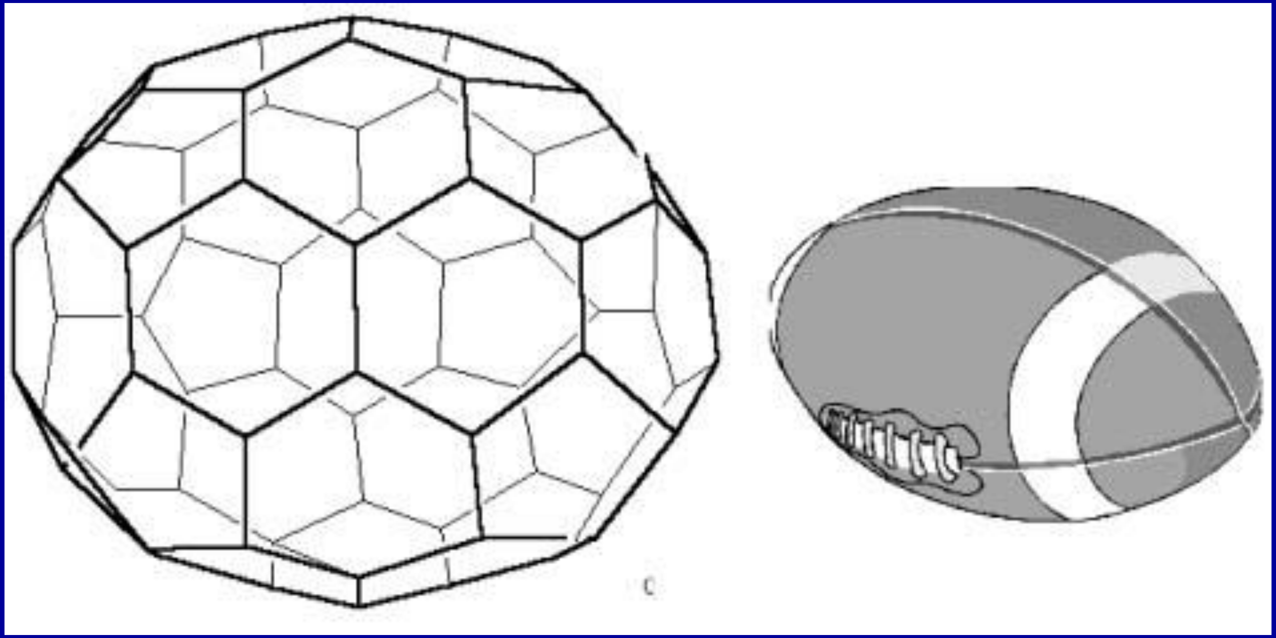


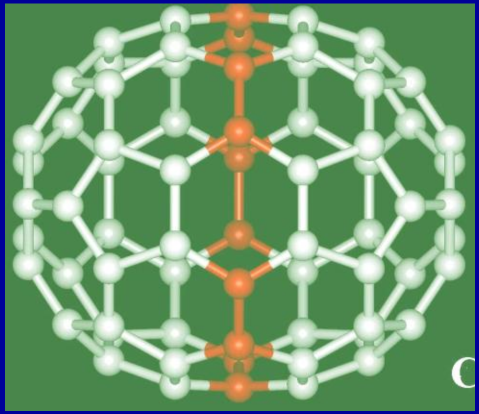
C_{60}



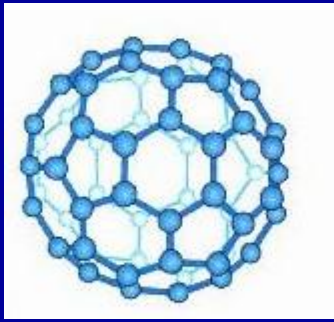
C_{70}

C_{70}

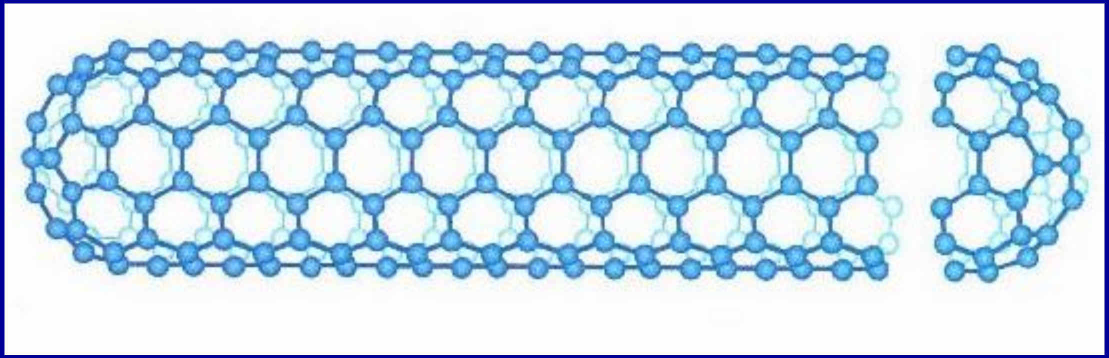


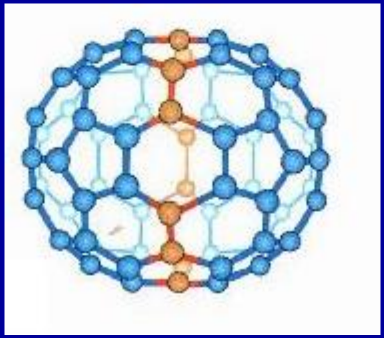


$C_{1000000}$ - carbon nanotube

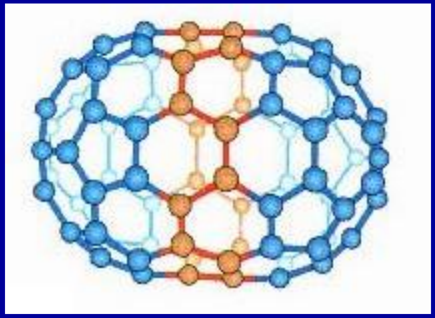


C_{60}



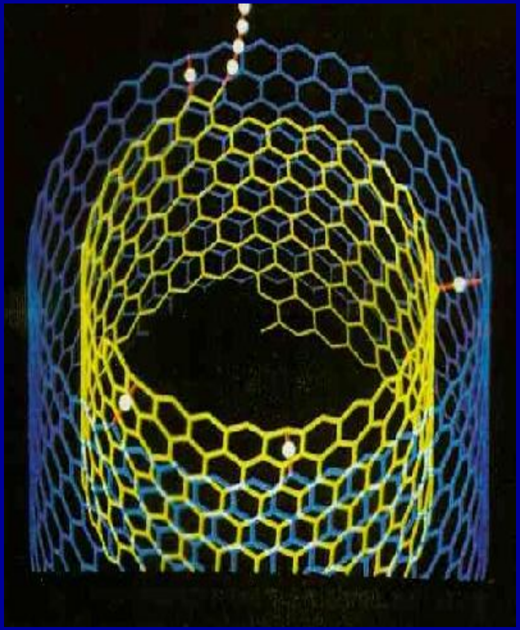


C_{70}



C_{80}

MWCN



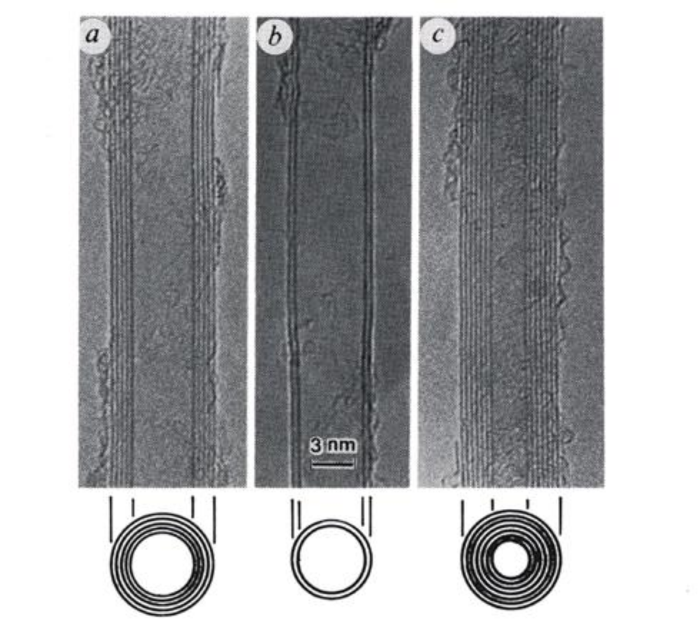
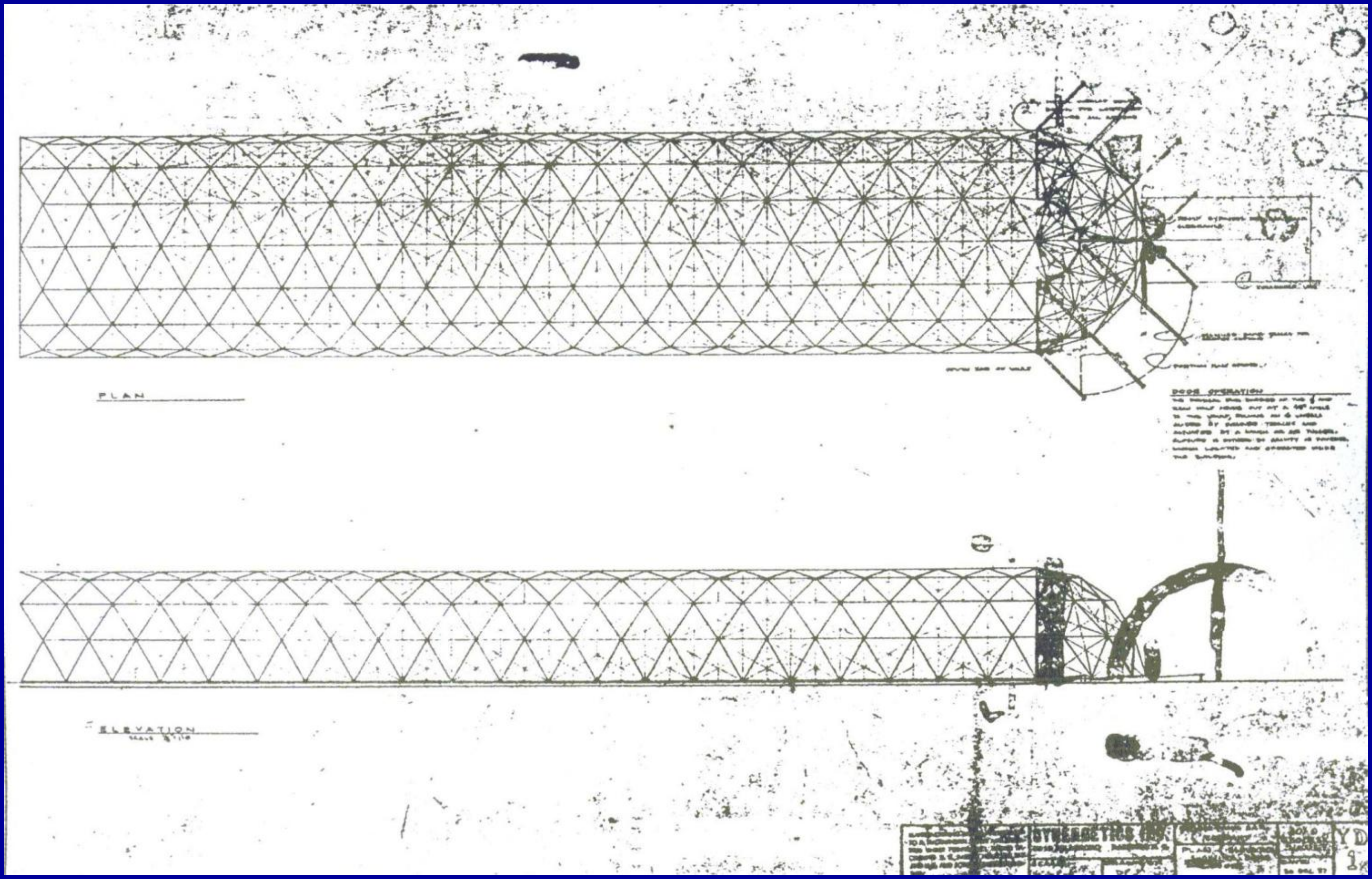
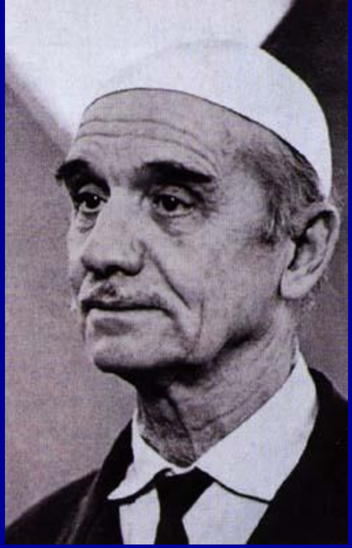


FIG. 1 Electron micrographs of microtubules of graphitic carbon. Parallel dark lines correspond to the (002) lattice images of graphite. A cross-section of each tubule is illustrated. *a*, Tube consisting of five graphitic sheets, diameter 6.7 nm. *b*, Two-sheet tube, diameter 5.5 nm. *c*, Seven-sheet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

S. Iijima, Nature 354 (1991) 56

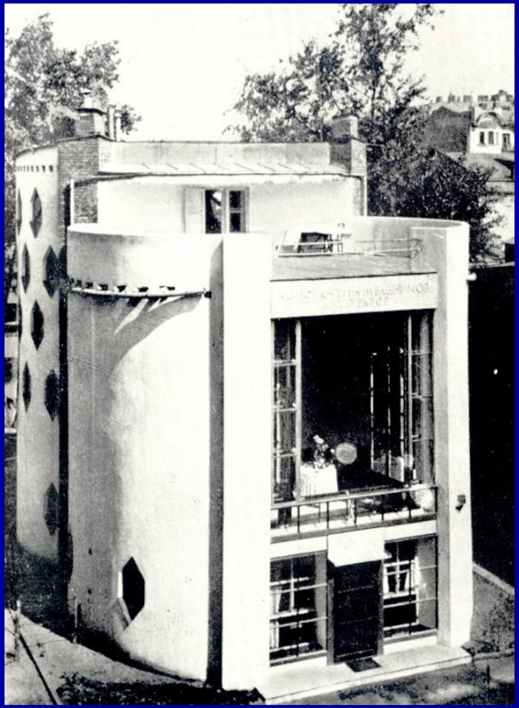


Buckminster Fuller's design for the entrance pavilion of the Union Tank Car Company

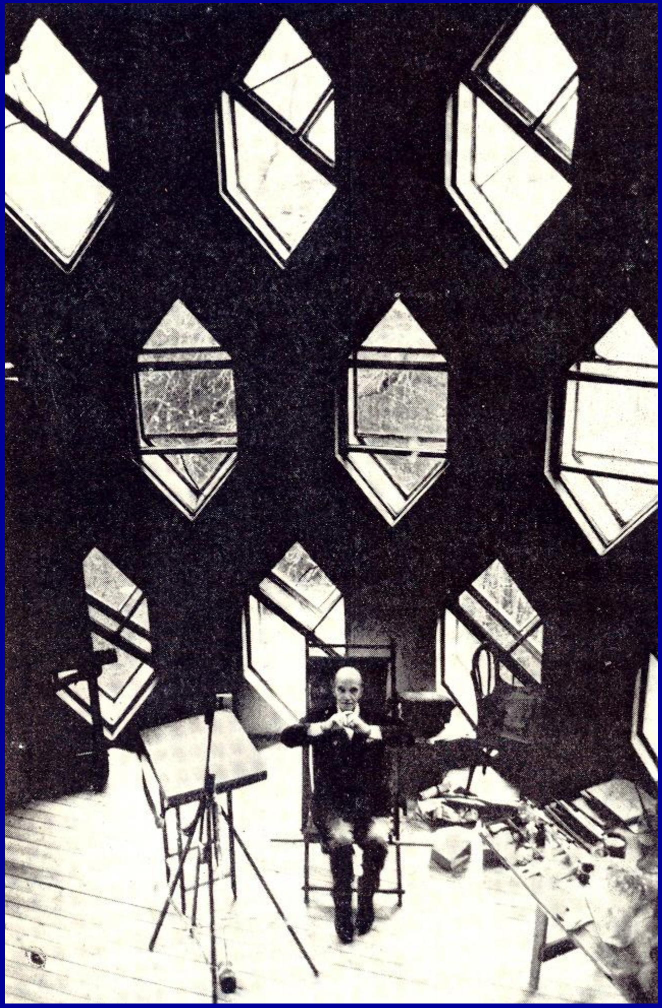


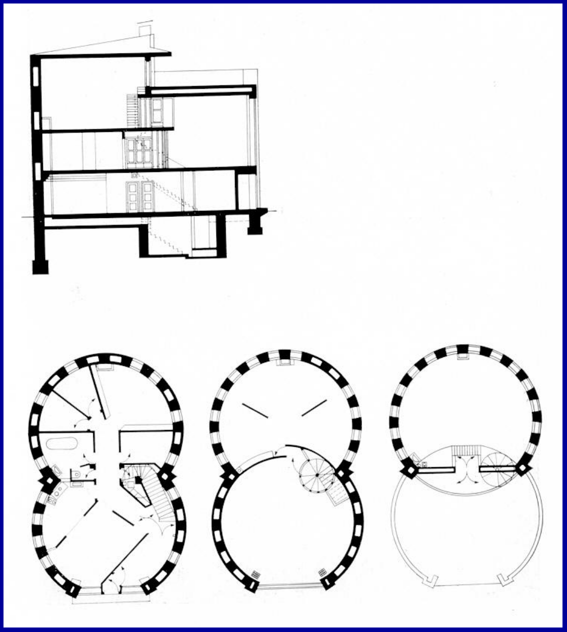
Konstantin Melnikov

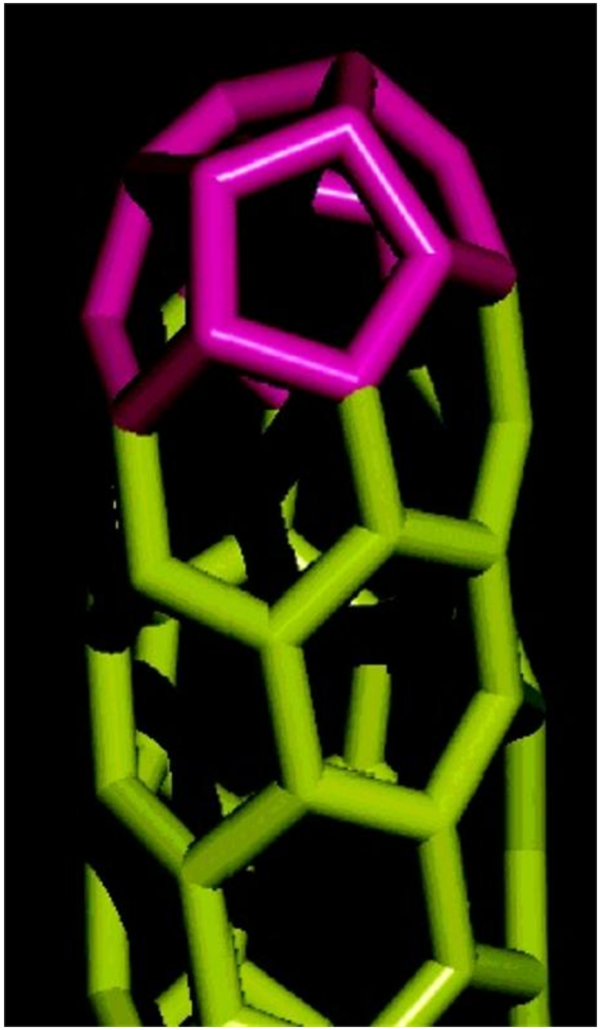
1890-1974



1927







CNT of smallest diameter (0.43 nm)

C_{20}

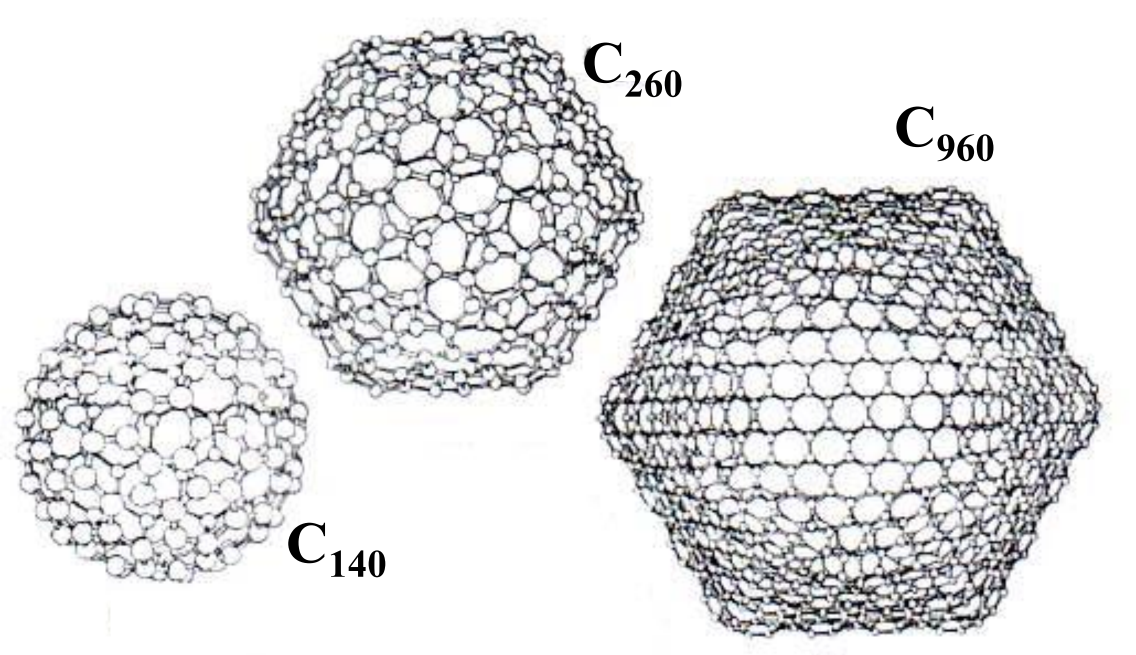
T. Hayashi, Y. A. Kim, T. Matoba, M. Esaka, K. Nishimura, T. Tsukada, M. Endo and M. S. Dresselhaus. *Nanoletters*, 3, 887 (2003).

Liverpool

Florence

Beer-Sheva

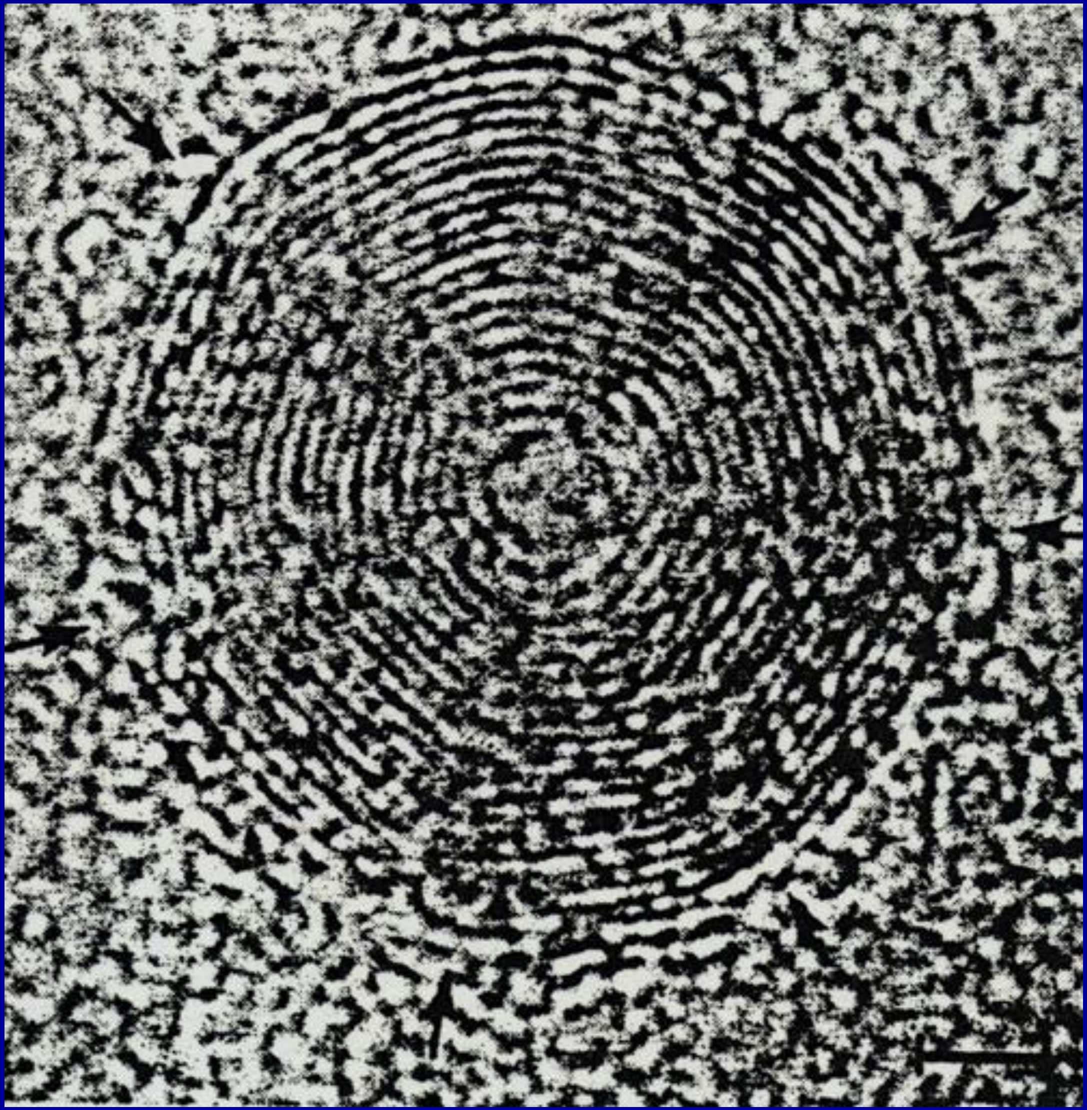
Nati Ziv studio



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).

Mail gilded guardian lions at the Forbidden City step their right front paws on an embroidered ball carved with a pattern of a fullerene (left) and a fullerene dual (right). Beijing, China, 1406-1420. Photo by E. Katz.

E. A. Katz and B.-Y. Jin. *Mathematical Intelligencer*, 38, 61 (2016).

fullerene

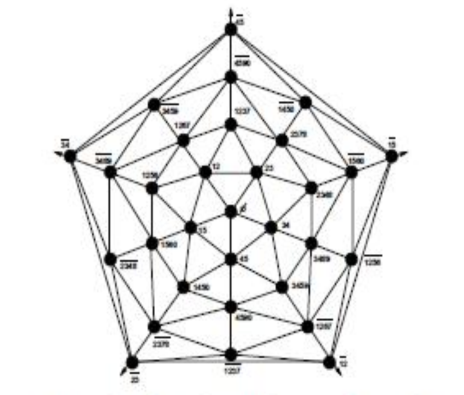
fullerene dual

fullerene

fullerene dual – deltahedron

(with 6- and 5-valent vertices)

Icosadeltahedron (C^*_{20T}): dual of an icosahedral fullerene



$C^*_{60}(I_h)$, $(a,b) = (1,1)$
pentakis-dodecahedron

Geodesic domes, viruses

Icosadeltahedra (dual fullerenes) in arhitecture

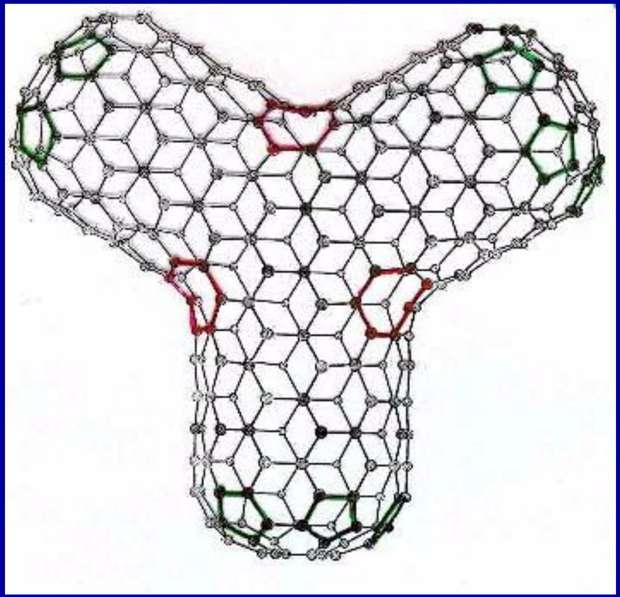
Fullerene	Geodesic dome
$F^*_{20}(I_h)$	One of Salvador Dali houses
$C^*_{60}(I_h)$	Artic Institute, Baffin Island
$C^*_{180}(I_h)$	Bachelor officers quarters, US Air Force, Korea
$C^*_{240}(I_h)$	U.S.S. Leyte
$C^*_{320}(I_h)$	Geodesic Sphere, Mt Washington, New Hampshire
$C^*_{500}(I_h)$	US pavilion, Kabul Afghanistan
$C^*_{720}(I_h)$	Radome, Artic dEW
$C^*_{3840}(I_h)$	Lawrence, Long Island
$C^*_{5120}(I_h)$	US pavilion, Expo 67, Montreal
$C^*_{6480}(I_h)$	Géode du Musée des Sciences, La Villete, Paris
$C^*_{6480}(I_h)$	Union Tank Car, Baton Rouge, Louisiana

Porta Marina Roman Baths, Ostia, first half of the II century

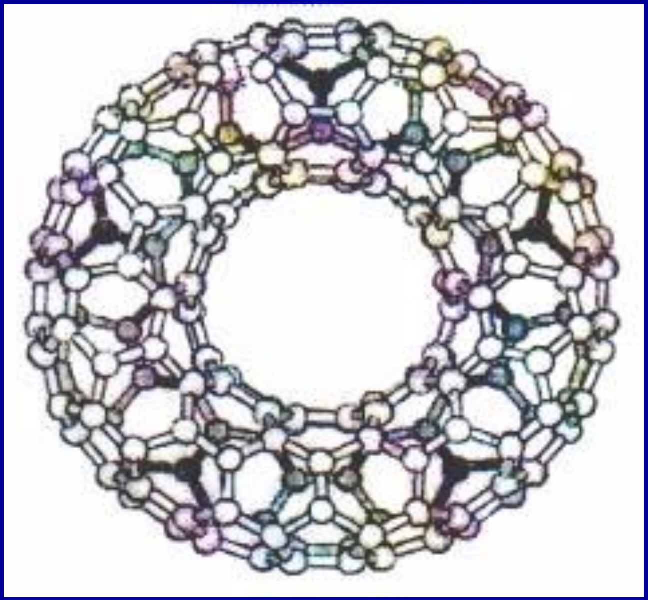
Photo by E. Katz

Fullerene-like structures with a negative curvature

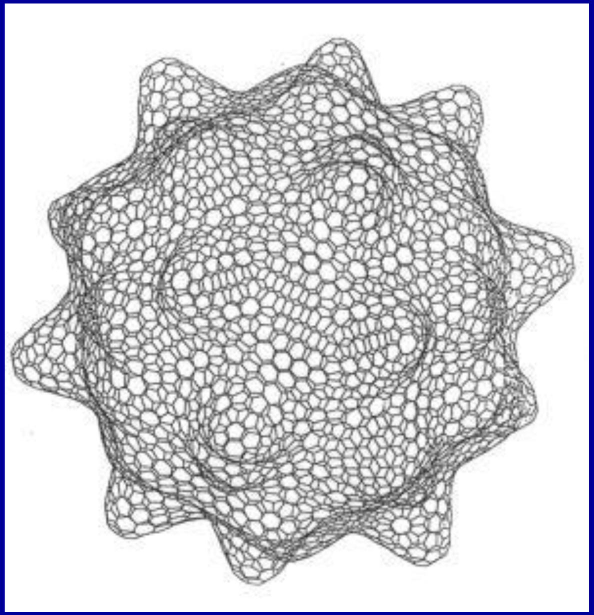
Pentagons, heptagons, hexagons



Y-nanotube

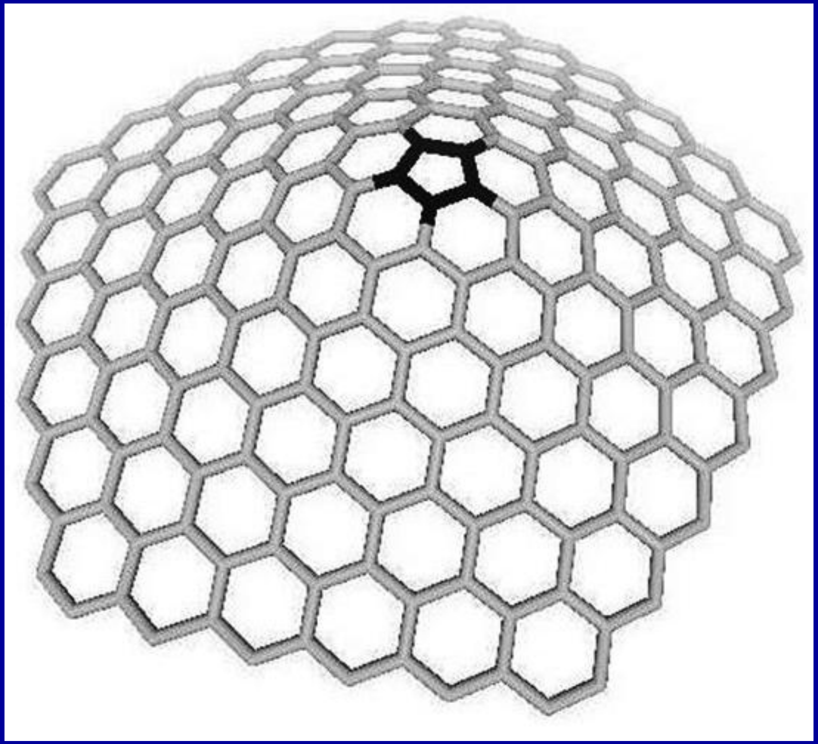


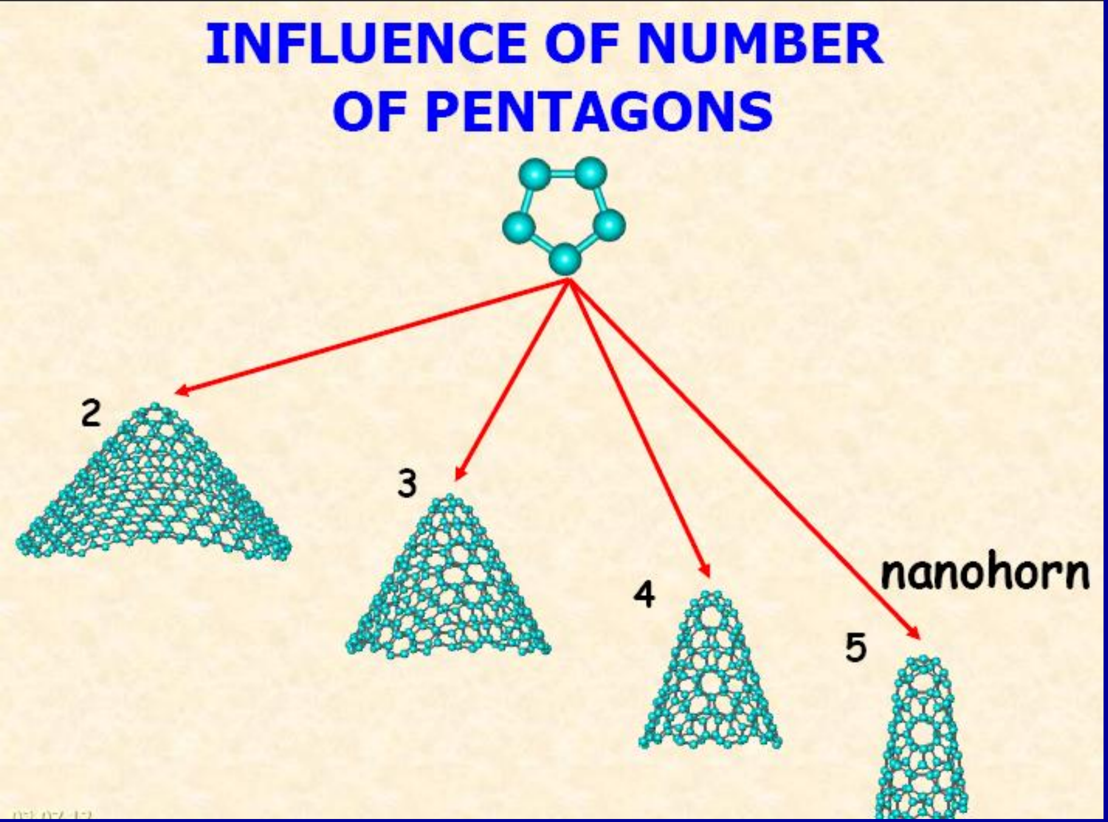
Carbon nano-torus



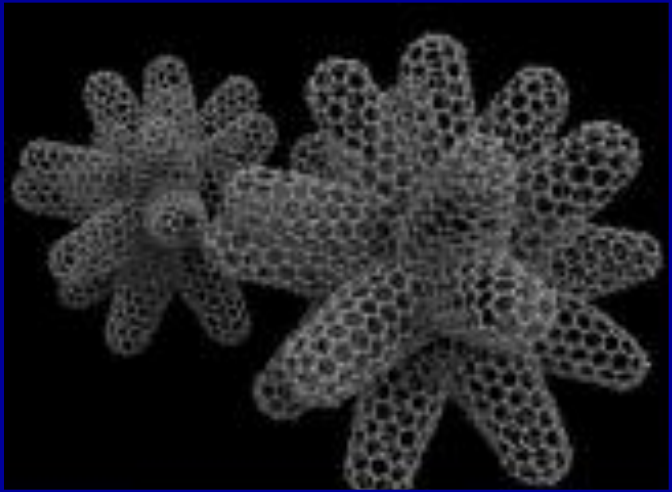
Star-like cluster

Carbon nano-cones



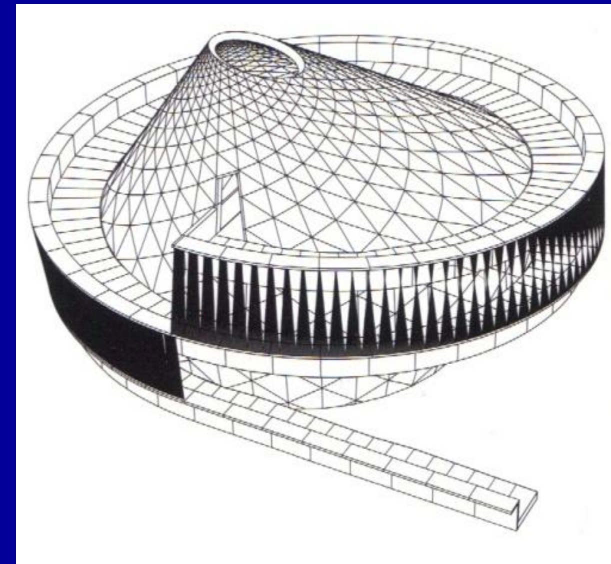


~100 nm

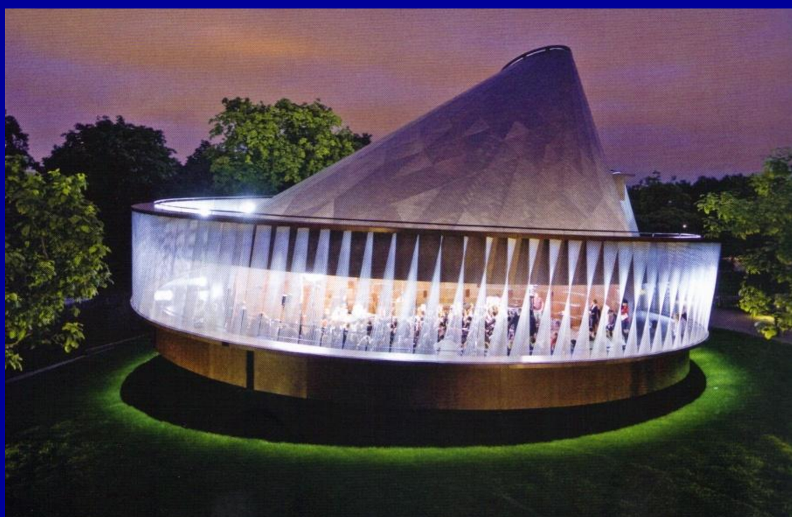


Kasuya D. et al. Selective production of single-wall carbon nanohorn aggregates and their formation mechanism. J. Phys. Chem. B, 2002, 106, 4947.

a



b



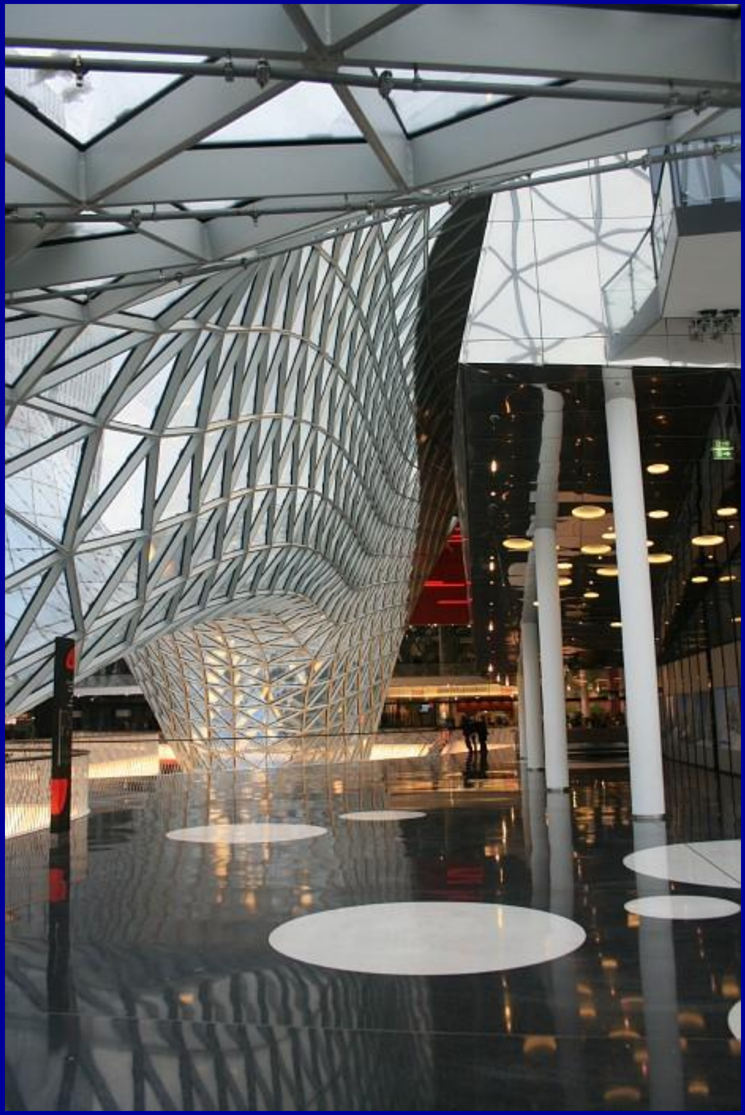
c

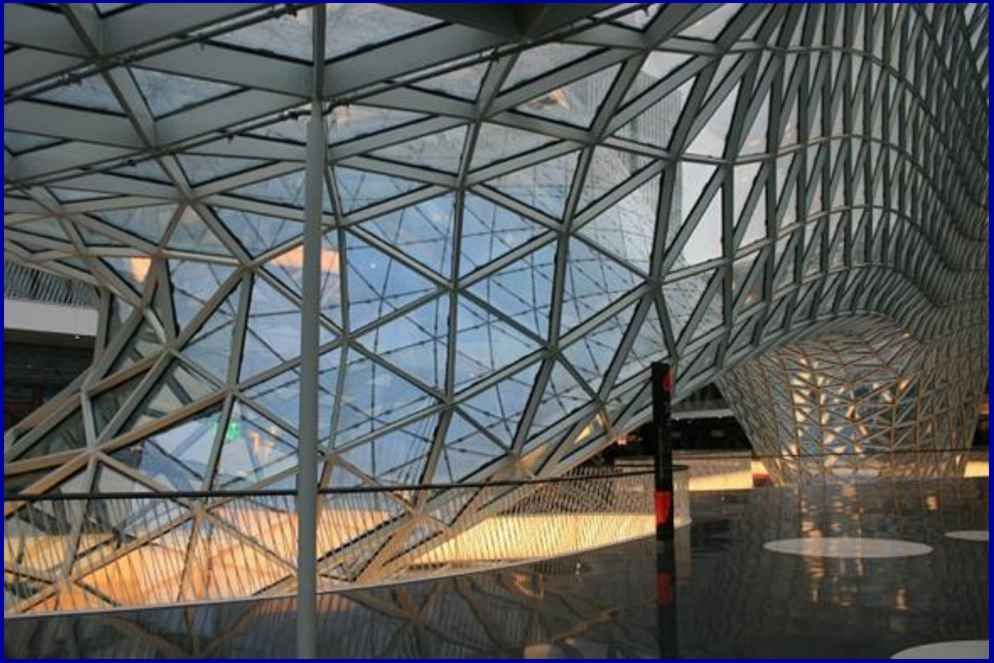
d

Architectural examples of conical geodesic-like structures. (a) Building of BMW Welt, Munich, Germany. Architect: Paul Kath, 2001-2007. (b-d) Serpentine Gallery pavilion, Kensigton Gardens, London. Architects: Olafur Eliasson and Kjetil Thorsen, 2001-2007.

Photos from [Architecture now! 6. TASCHEN, 2009]

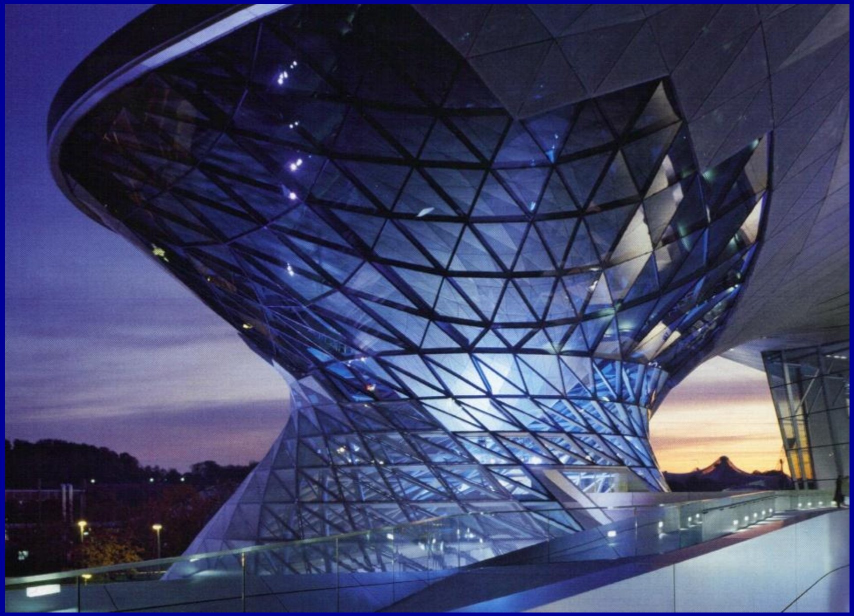
Architectural geodesic-like structures with negative curvature (1)





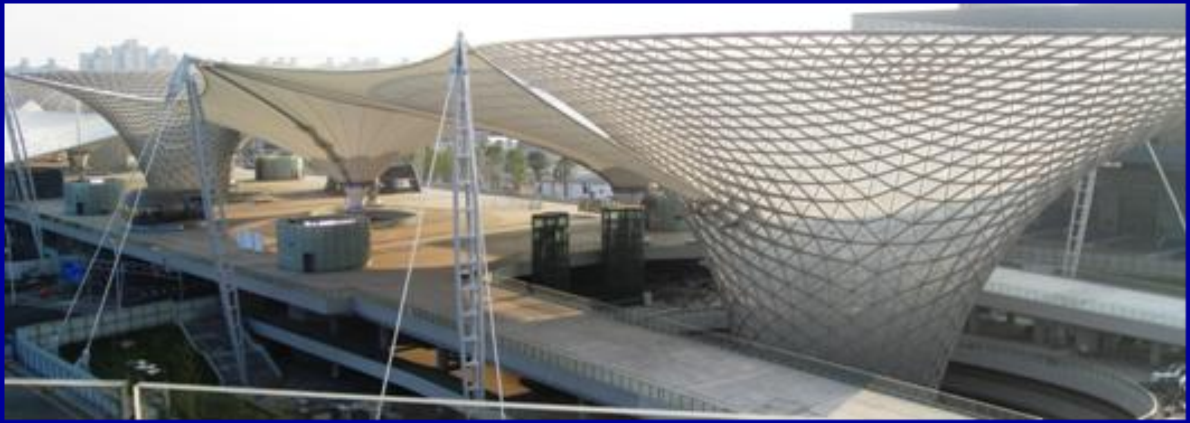
Supermarket MyZeil, Frankfurt. Architect: Massimiliano Fuksas (2009). Photo by M. Sazonov. With permission by M. Sazonov

Architectural geodesic-like structures with negative curvature (2)



Building of BMW Welt, Munich, Germany. Architect: Paul Kath, 2001-2007. Photo from [Architecture now! 6. TASCHEN, 2009]

Architectural geodesic-like structures with negative curvature (3)



“Expo-axis” at the Expo 2010, Shanghai, China.

Photo by E.Katz

"Expo Axis" was the main building at the Expo 2010 in Shanghai built by SBA (architects) and Knippers Helbig (structural engineers).

Photo from [http://en.wikipedia.org/wiki/Expo_2010]

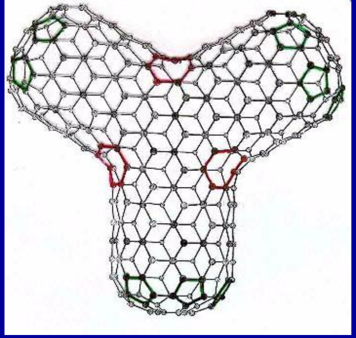
Architectural geodesic-like structures with negative curvature (4)

Museo Soumaya,
Mexico City,
architect Fernando Romero

Pillow-like structures

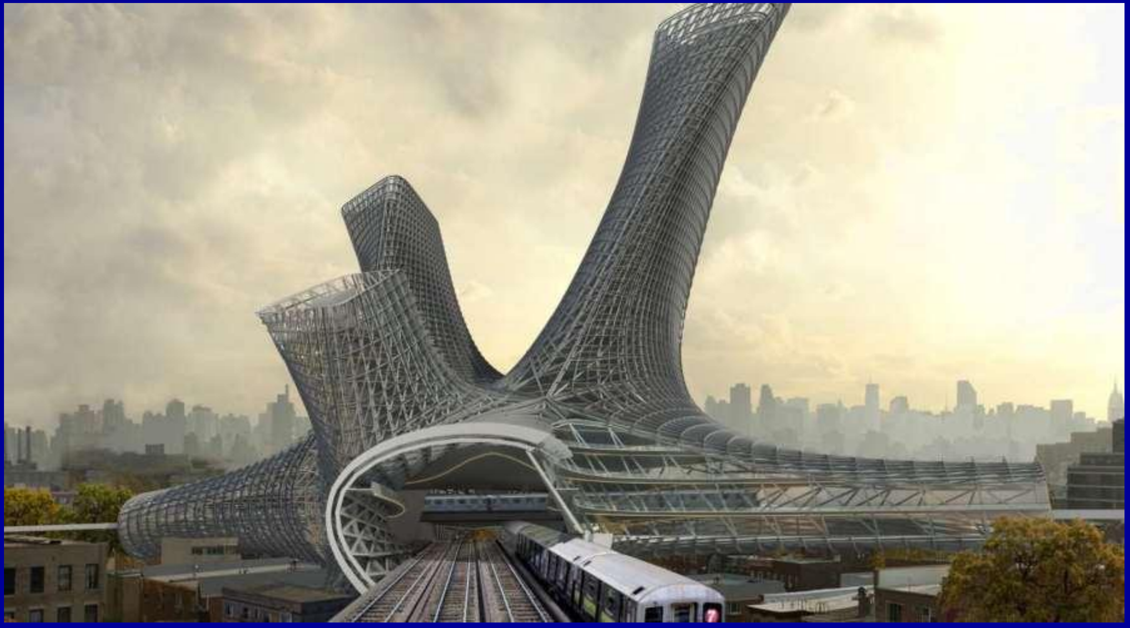
Eindhoven, The Netherlands. Photo by E. Katz

Y-nanotube



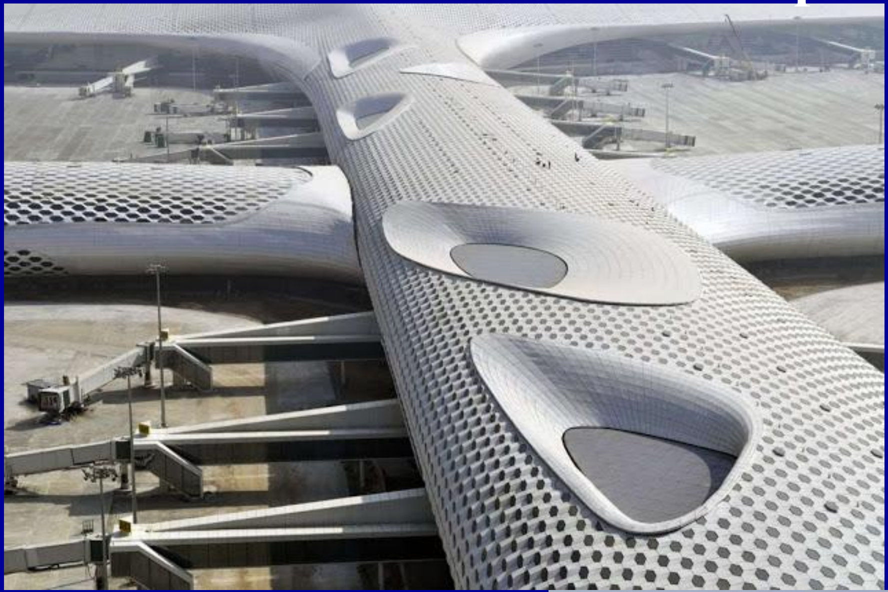
Project:
URBAN ALLOY TOWERS, NY (AMLGM, 2014)

Residential typology rooted in the remnant spaces surrounding the intersection of transportation infrastructure, such as elevated train lines and
freeway interchanges.
In this space urban citizens can work, play, eat and rest within a pedestrian zone.



Terminal 3, Shenzhen International Airport, China (FUKSAS, 2013)

The sculptural 500,000 sq.m. terminal with 63 contact gates (1.5 km long, with roof spans of up to 80m).

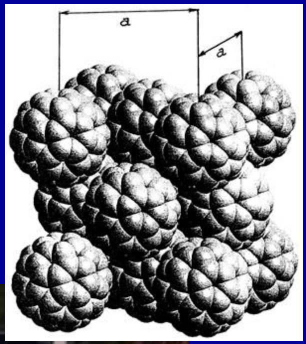


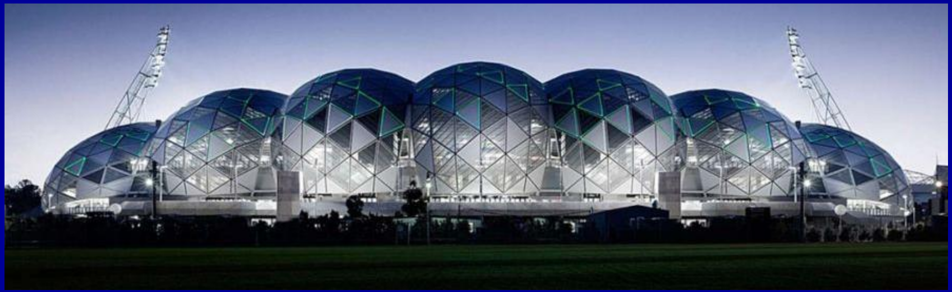
Honeycomb shaped metal and glass panels allow natural light to filter through

AAMI Park, Melbourne, Australia (Architect: Cox Architecture, 2010)

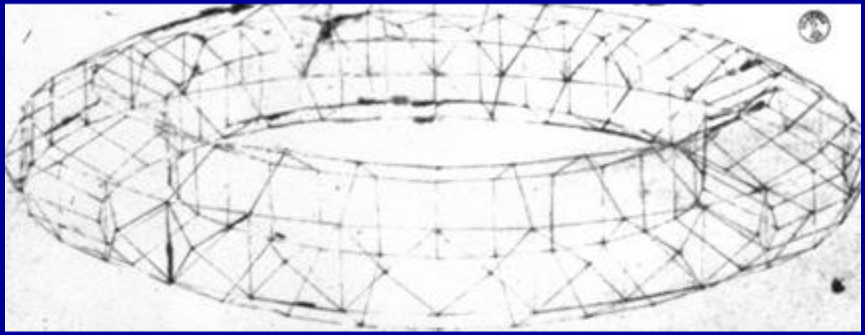
Multi-code sport campus (facility for 4 separate football stadiums, for example)

Fullerite





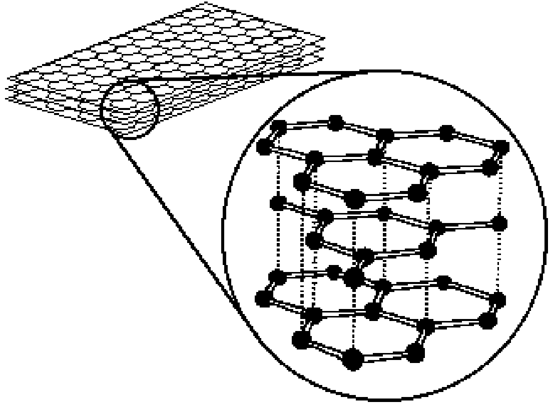
Polyhedral tori (mazzocchio) by Paolo Uccello (1397-1475)



Ubriachi chapel,
Santa Maria Novella,
Florence,
Photo by E. Katz

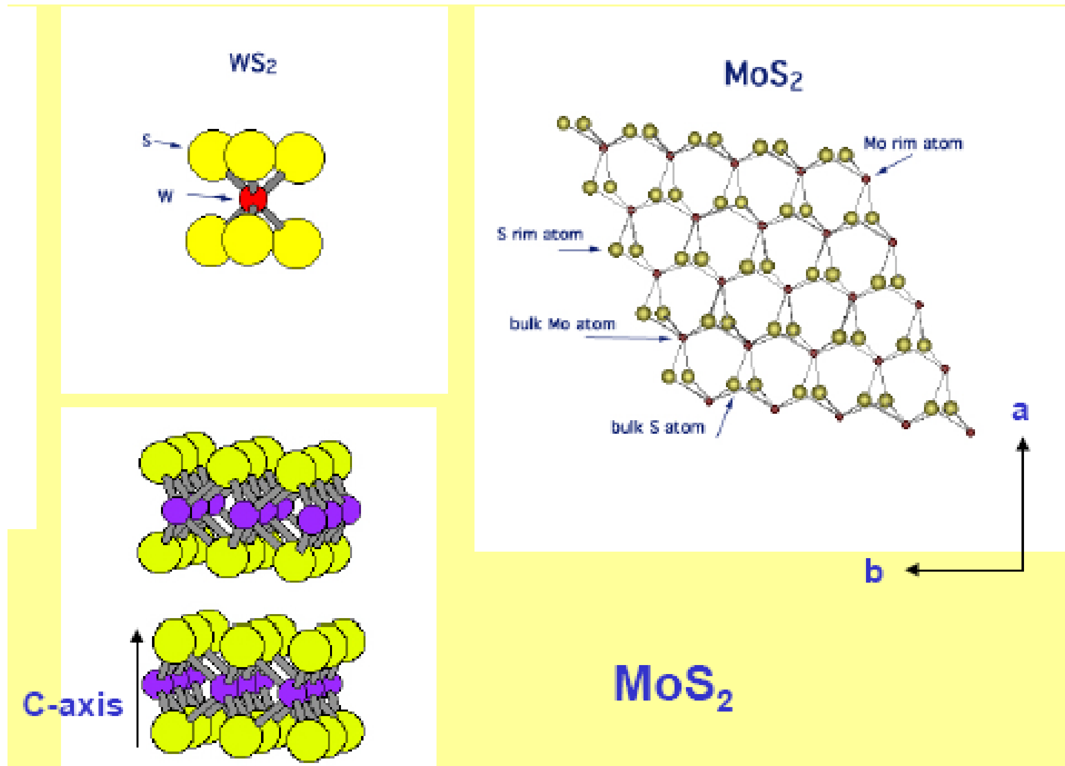
Is it possible to build fullerenes from other elements?

Non-carbon (inorganic) fullerenes?



Graphite

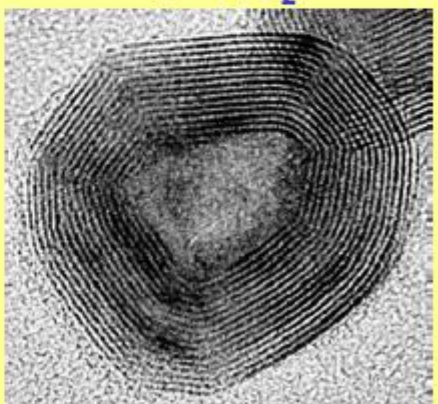
Inorganic nanotubes and fullerene-like particles from 2-D layered compounds



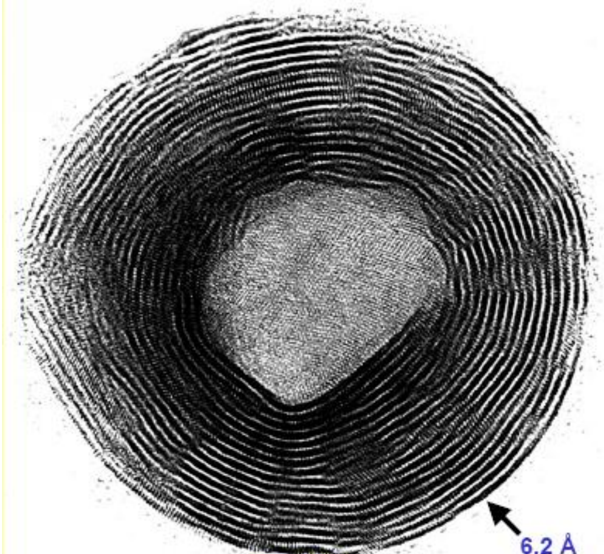
R.Tenne and co-workers, *Nature*, 360, 444 (1992); 365, 113 (1993); *J. Am. Chem. Soc.*, 116, 1914 (1994); *Science*, 267, 222 (1995)

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

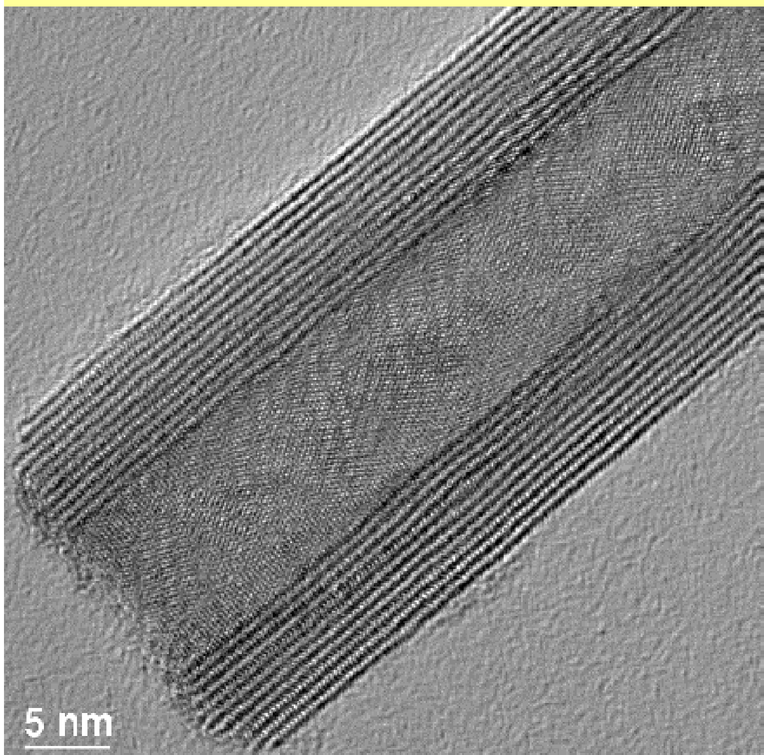


IF-MoS_2



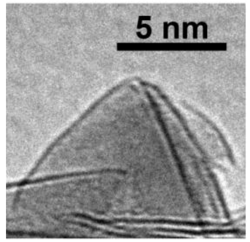
IF-WS_2

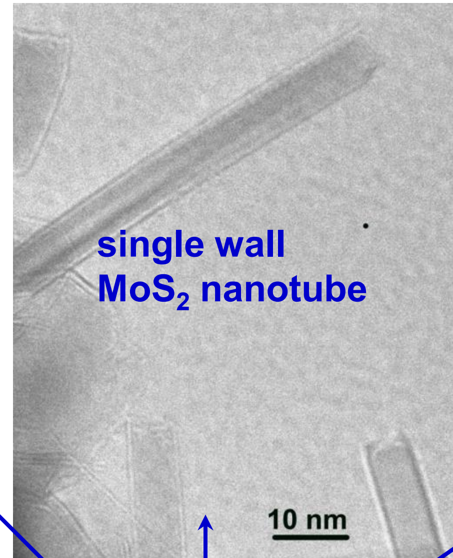
Multiwall WS_2 nanotube

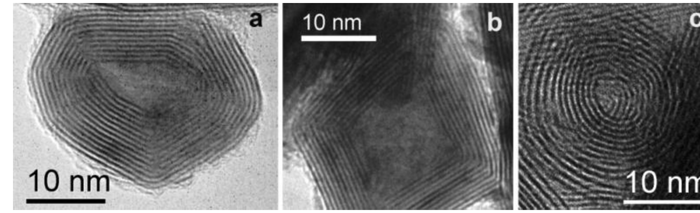


Inorganic (non-carbon fullerenes)

MoS$_2$ fullerene-like nanoparticle



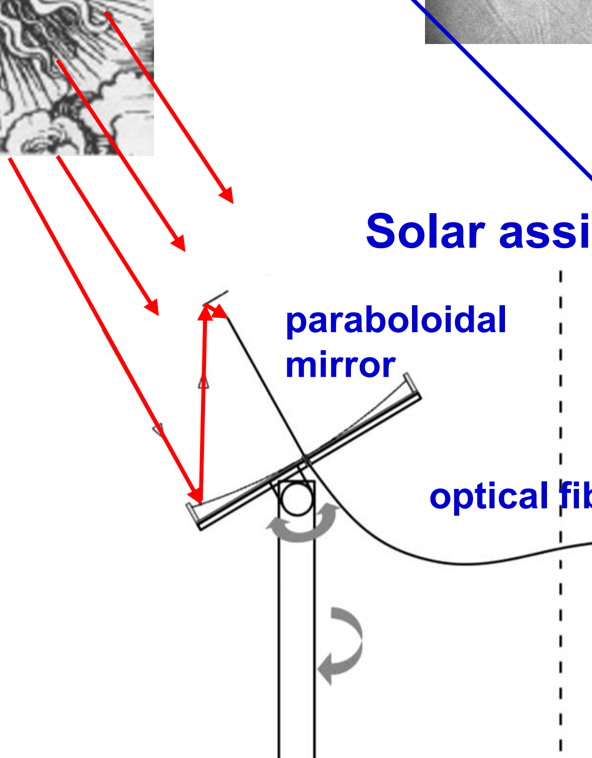


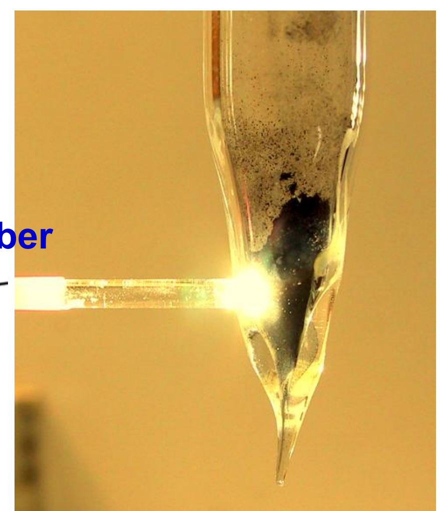


Nested Cs$_2$O fullerenes

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

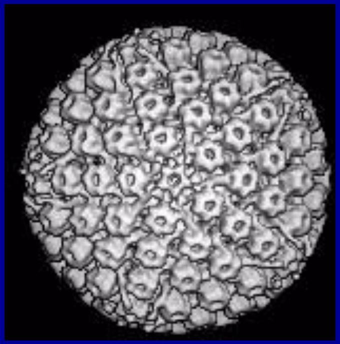


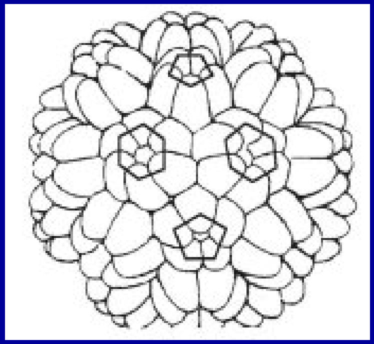


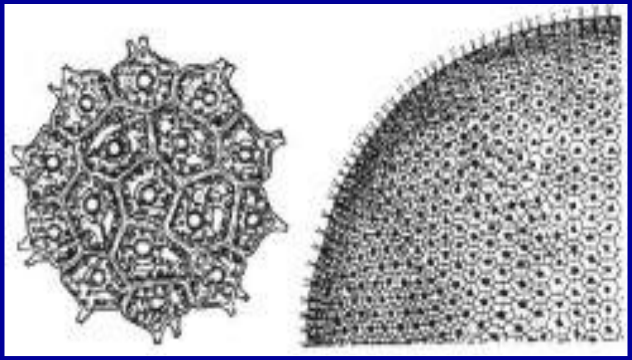
J. M. Gordon, E. A. Katz, D. Feuermann, A. Albu-Yaron, M. Levy, R. Tenne. ***Journal of Materials Chemistry***, 18, 458 (2008).

Fullerene-like structures in animate nature

Fullerene-like viruses







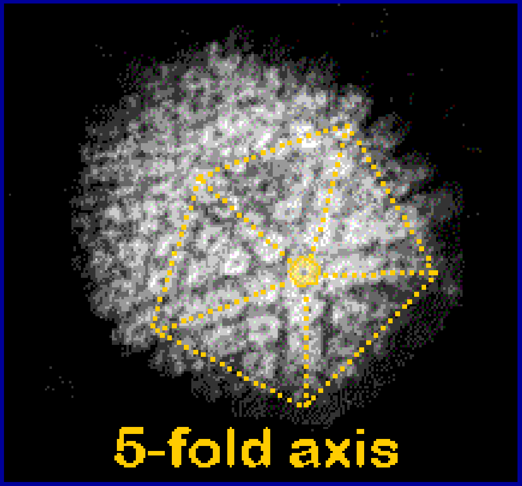
Herpes

20-300 nm

Could viruses be considered as living organisms?

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

No: they have no cell structure

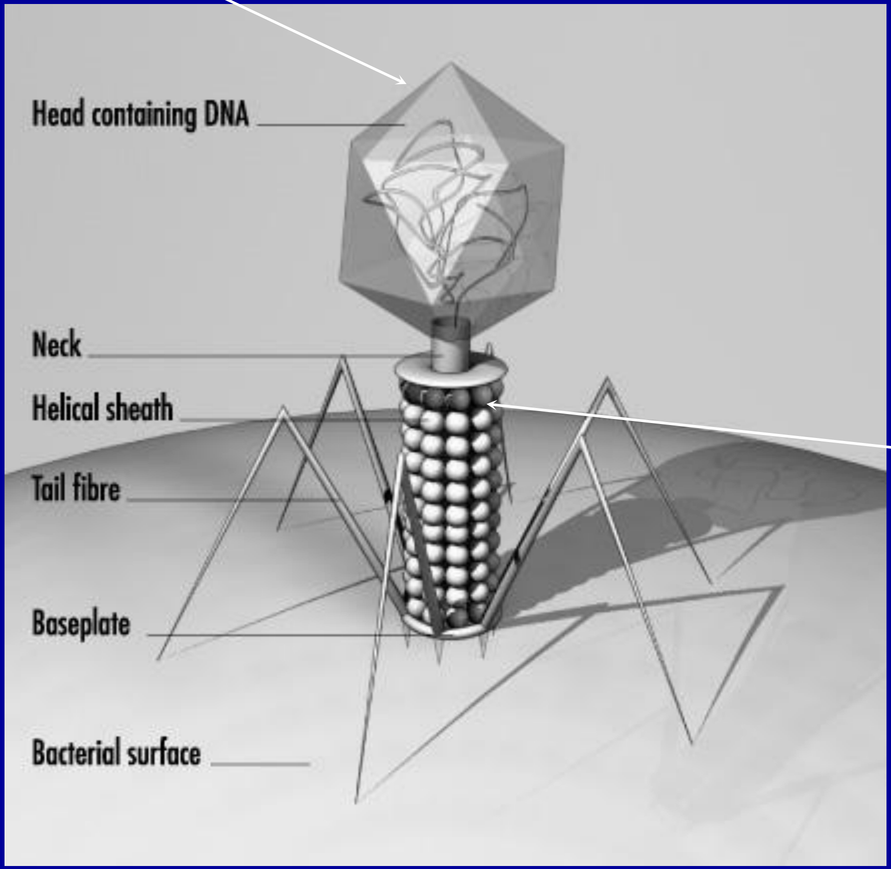


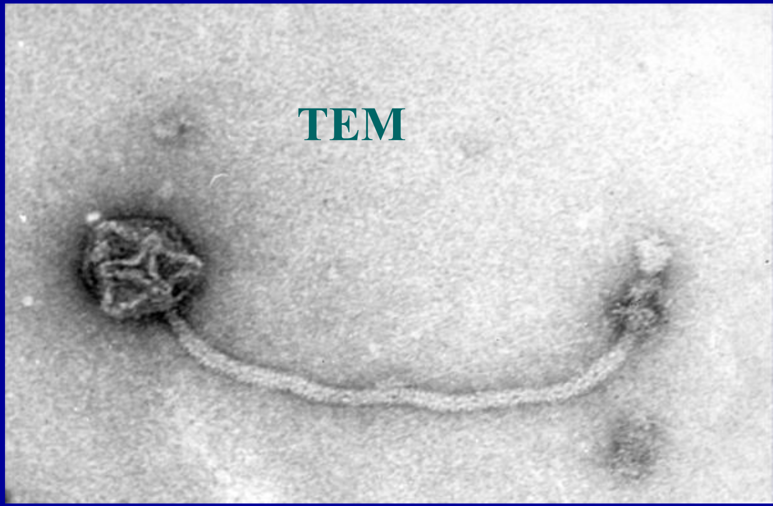
Viruses are on the very boundary between animate and abiotic nature.

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

Discovered by Félix d'Hérelle, 1917

40-140 nm





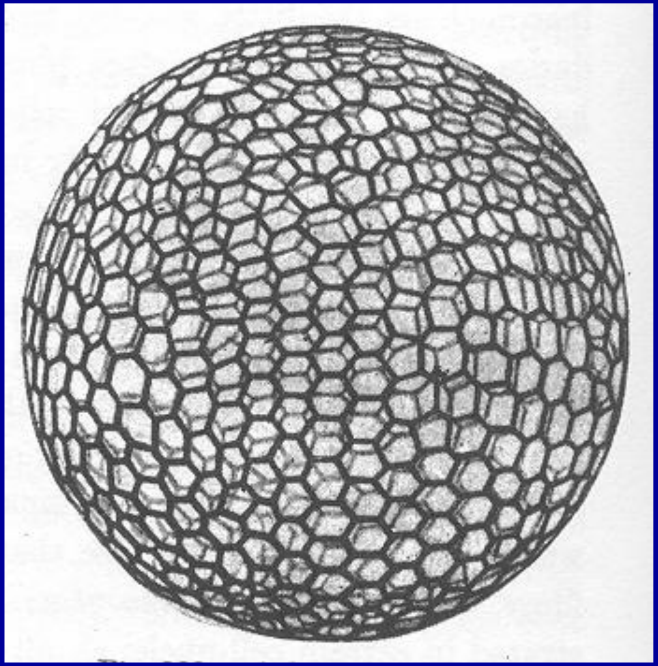
Nanotubes (10-40 nm diameter, 100-200 nm length)

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

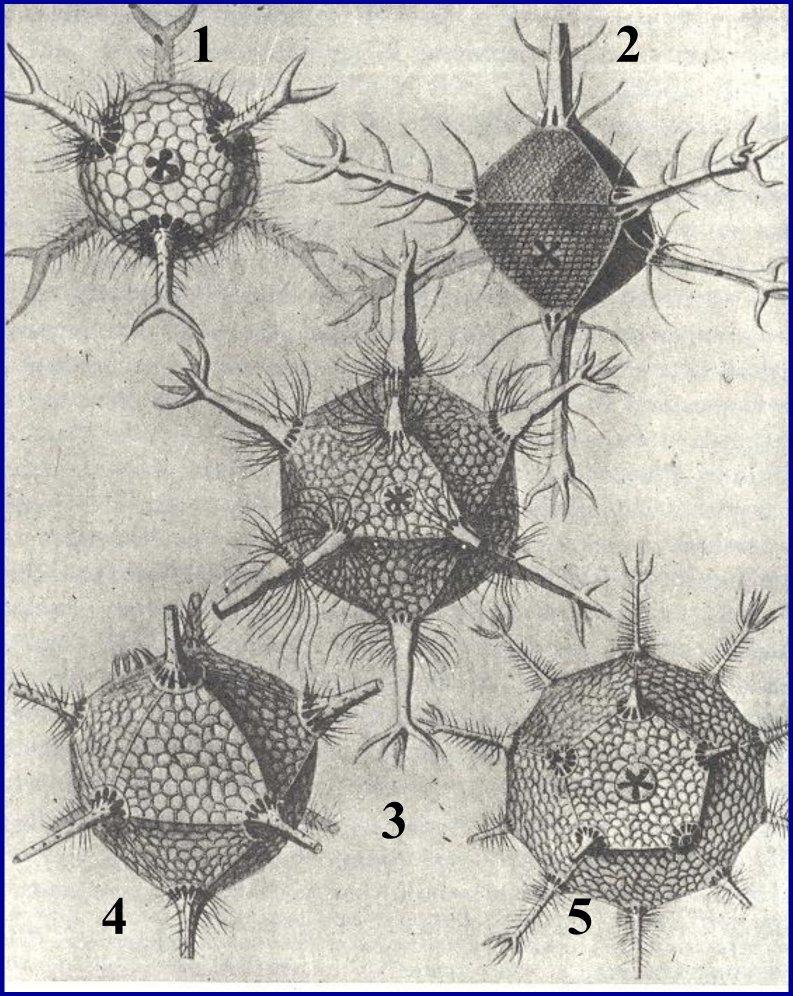
Phage therapy

Radiolaria

40 μ m – 1mm



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



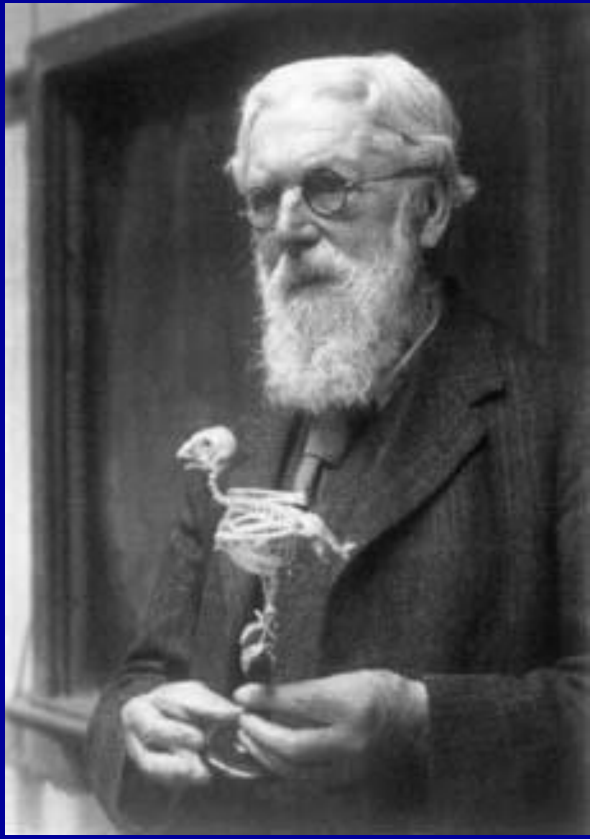
Skeletons of various radiolarians: 1. *Cicroporus sexfurcus*, 2. *C. octahedrus*, 3. *Circogonia icosahedra*, 4. *Cicrospathis novena*, 5. *Cicrorrhegma dodecahedra*.
From: E. Haeckel "Monograph of the Challenger Radiolaria", 1987.

$F - E + V = 2$

$p = 12$

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

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; 2nd ed., 1942; posthumous 3rd ed., 1952; 4th ed., 1959; 5th ed., 1963, 6th ed., 1992.

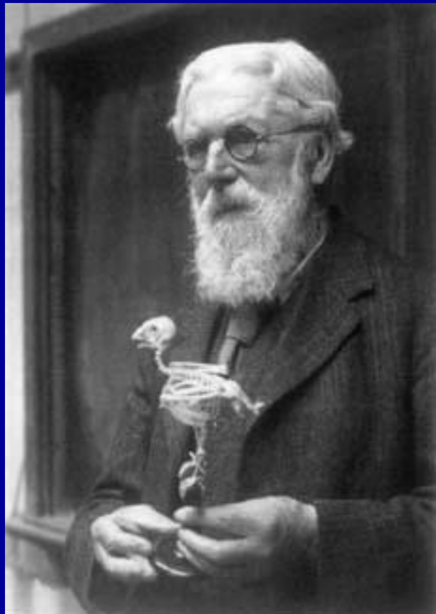
Scientific relay race:
D'arcy Thomson → Jones → Iijima → Kroto

Dmitry D. Morduhai-Boltovskoi (1876–1952):

1906

Prominent mathematician, historian of mathematics, philosopher
(with a strong background in classics);
the author of the 1st complete, definitive translation of Euclid's *"Elements"* into Russian (1948-50)

http://pyrkovve.narod.ru/index.html

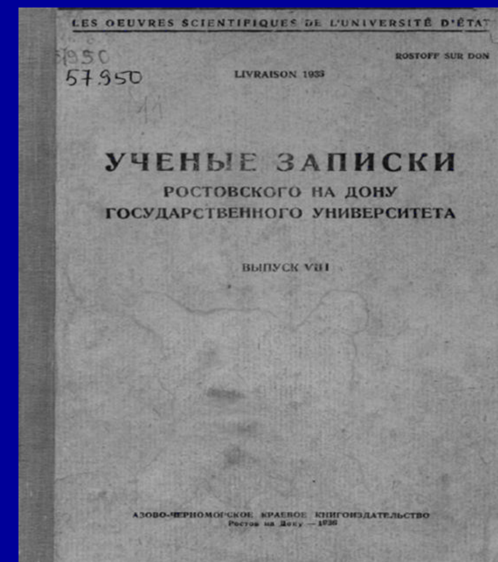


D’arcy W. Thomson

“On Growth and Form”,

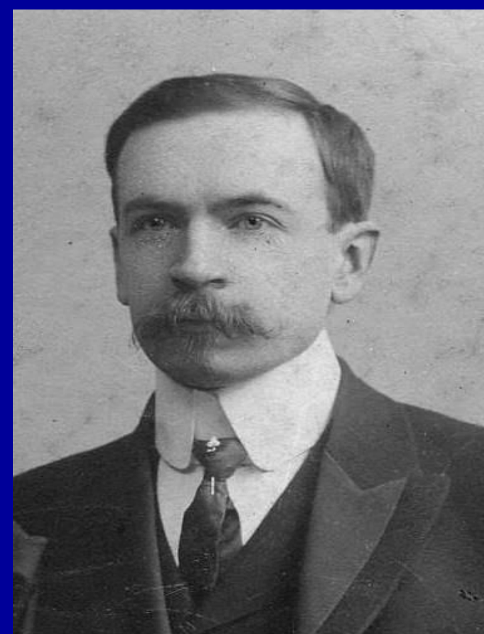
Cambridge Univ. Press, ~~1917~~;

2nd ed., 1942;



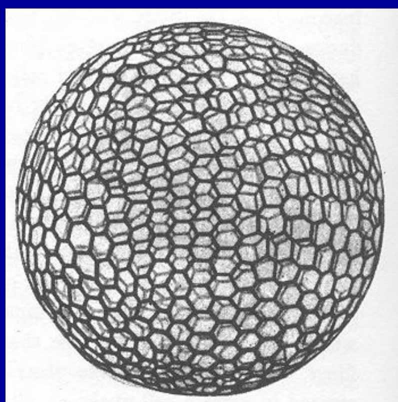
D. D. Morduhai-Boltovskoi

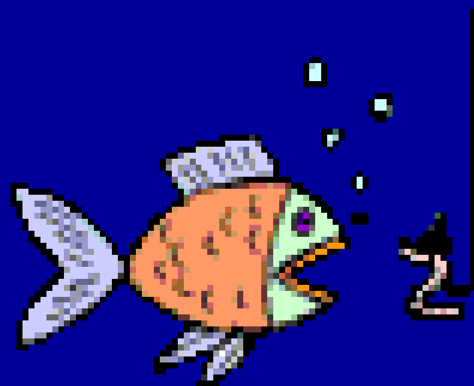
“Geometry of Radiolaria”, 1936

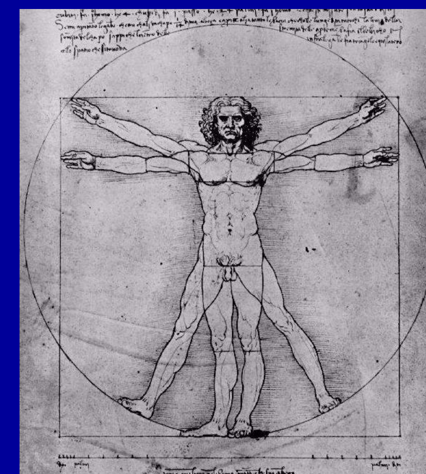


E. A. Katz. *Mathematical Intelligencer*, 36, 34 (2014).

Evolution of living organisms







Decrease of symmetry

Thanks a lot for your attention!