

# Composti Policiclici Aromatici e forme allotropiche del carbonio

## COMPOSTI AROMATICI POLICICLICI

Quando il carbone viene riscaldato a 1000 °C in assenza di aria subisce una scissione termica. In queste condizioni evapora una miscela di prodotti volatili chiamati **catrame di carbone**. L'ulteriore distillazione frazionata del catrame di carbone fornisce i seguenti composti:

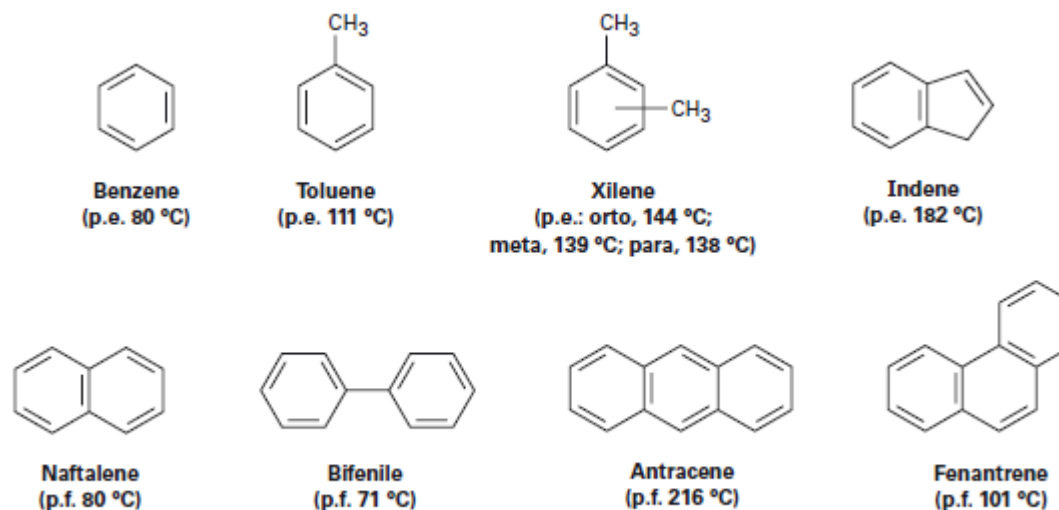
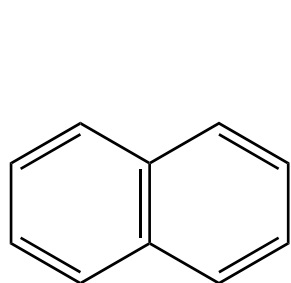


Figura 15.1 Alcuni idrocarburi aromatici presenti nel catrame di carbone.

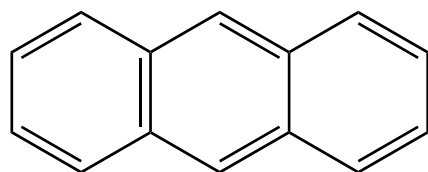
## COMPOSTI AROMATICI POLICICLICI

---

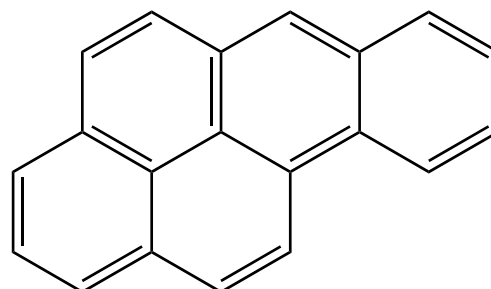
Il concetto generale di aromaticità può essere esteso anche ai composti aromatici policiclici



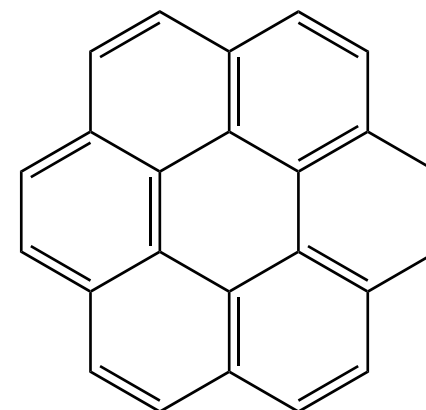
naftalene



antracene

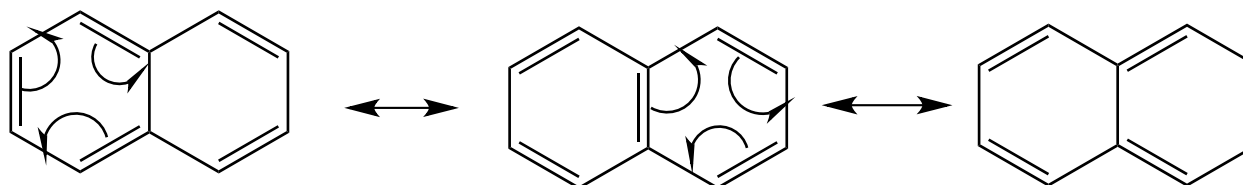


benzo[a]pirene



coronene

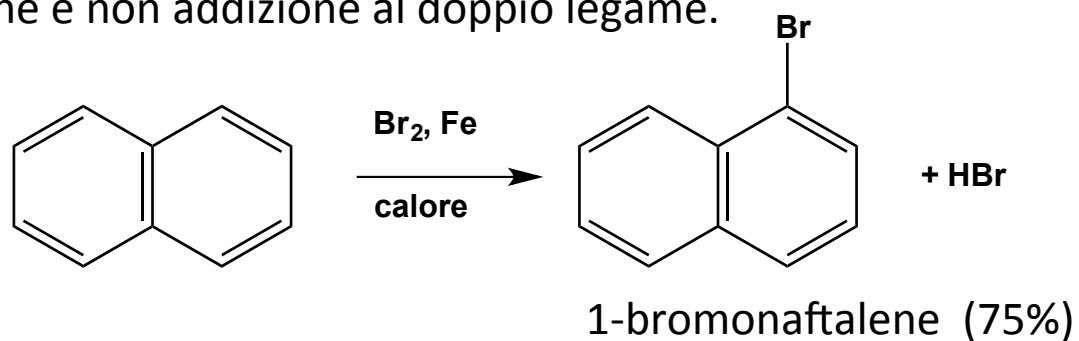
il naftalene ha 3 forme di risonanza



il calore di idrogenazione mostra una energia di stabilizzazione aromatica di 250 kJ/mol (60 kcal/mol)

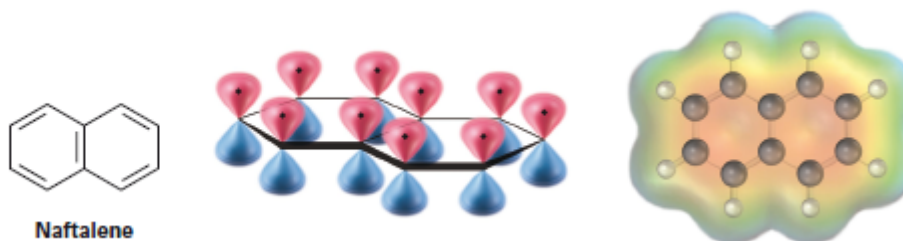
## COMPOSTI AROMATICI POLICICLICI

reattività: il naftalene reagisce lentamente con elettrofili fornendo prodotti di sostituzione e non addizione al doppio legame.



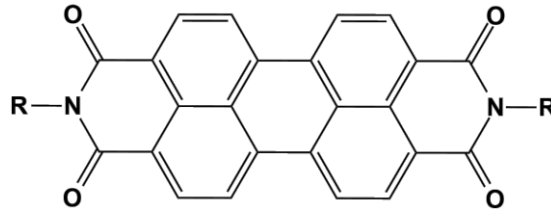
gli elettroni sono delocalizzati su entrambi gli anelli

**Figura 15.10** Il disegno degli orbitali e la mappa di potenziale elettrostatico del naftalene mostrano che i dieci elettroni  $\pi$  sono completamente delocalizzati su entrambi gli anelli.



## Perché sono interessanti questi composti

Es.

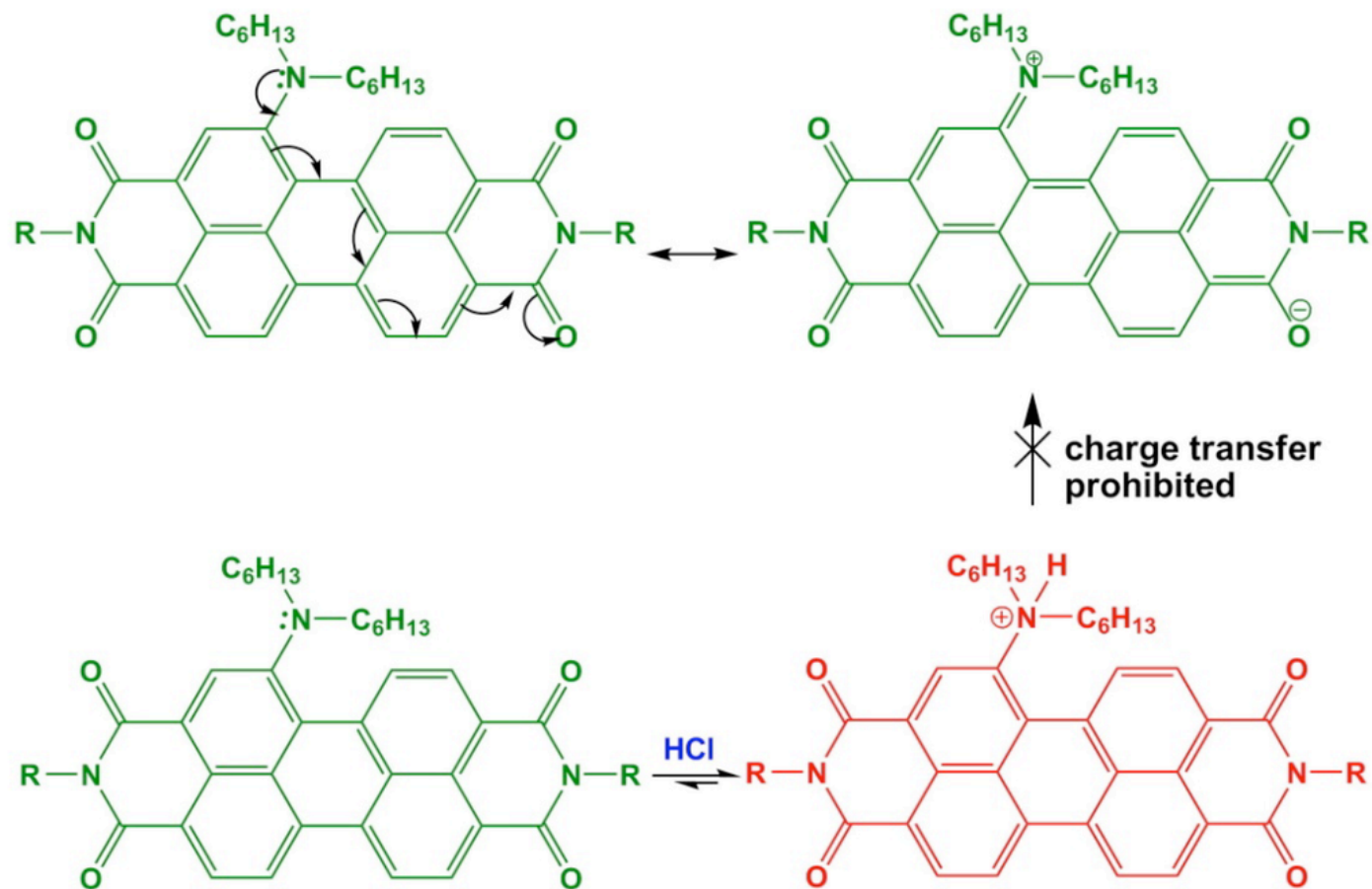


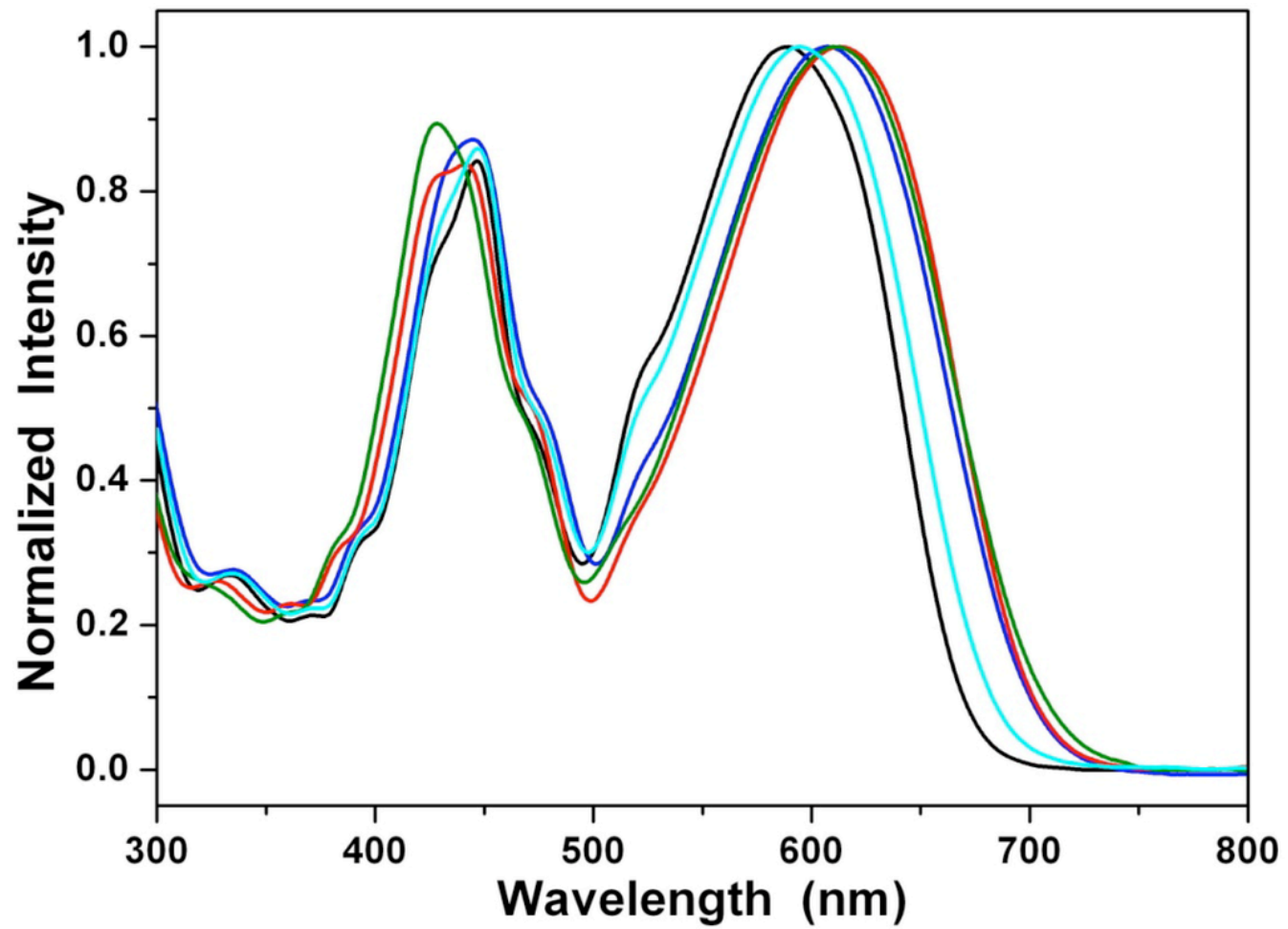
Organic Dyes

General structure of a **perylene bisimide** molecule (PBI).

These polycyclic aromatic molecules have been considered for their exceptional features: they have (i) a strong absorption in the visible region ( $400 < \lambda < 700$  nm) with a nearly unity quantum yield, (ii) a high thermal and oxidative stability, (iii) high electron mobility, (iv) sustainable costs of the raw materials, and (v) supramolecular self-assembling properties leading to the formation of functional architectures, due to the  $\pi$ -stacking between neighbouring molecules. In addition, due to the easy tunability of the HOMO and LUMO levels, PBIs has been already used in the field of organic electronics since they exhibit n-type semiconducting properties (reach of electrons).

These molecules show intense green color in both solution and solid state and are highly soluble in dichloromethane and even in nonpolar solvents, such as hexane

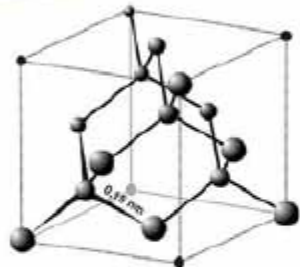




UV-Vis spectra in different solvents

# COMPOSTI AROMATICI POLICICLICI

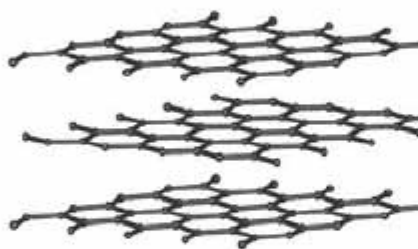
Forme allotropiche del carbonio



Diamante

materiale noto per la sua durezza

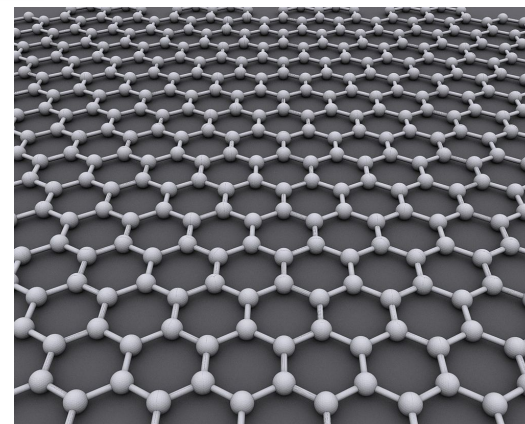
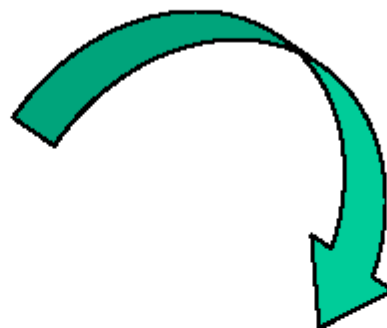
si forma a temperature comprese fra i 900 °C ed i 1.200 °C e pressione di circa 50 kbar



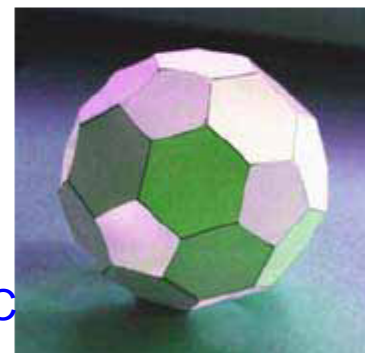
Grafite

materiale con elevata conduttività elettrica

si forma alla temperatura di 1.200 °C



Grafene



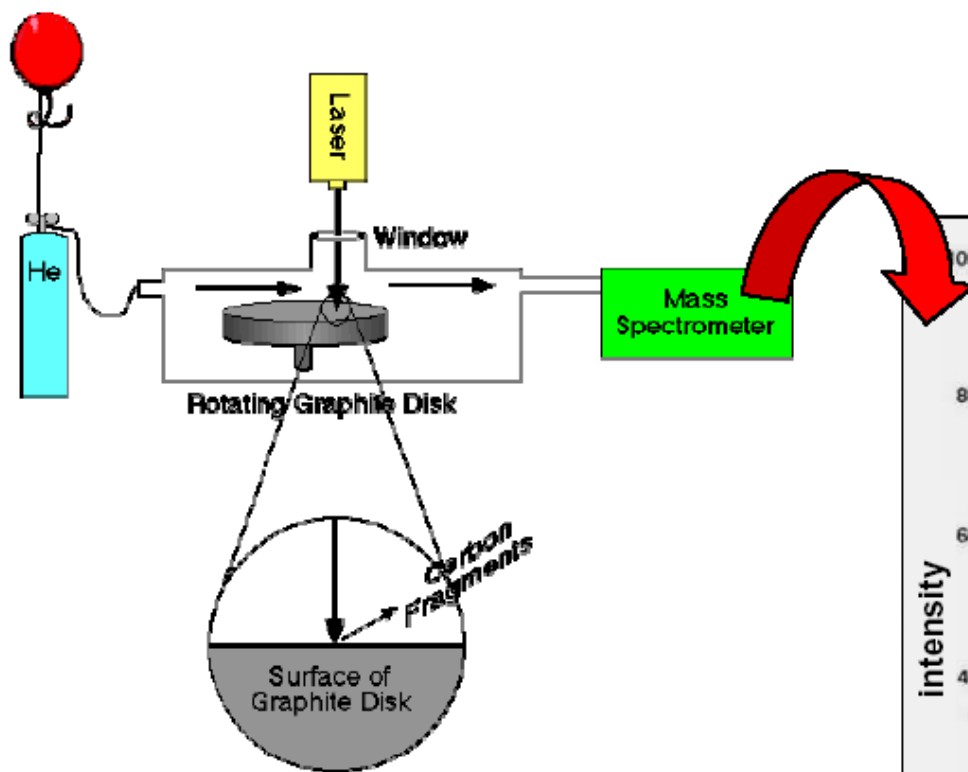
1970

Eiji Osawa la teorizza  
R.W.Henson la propone

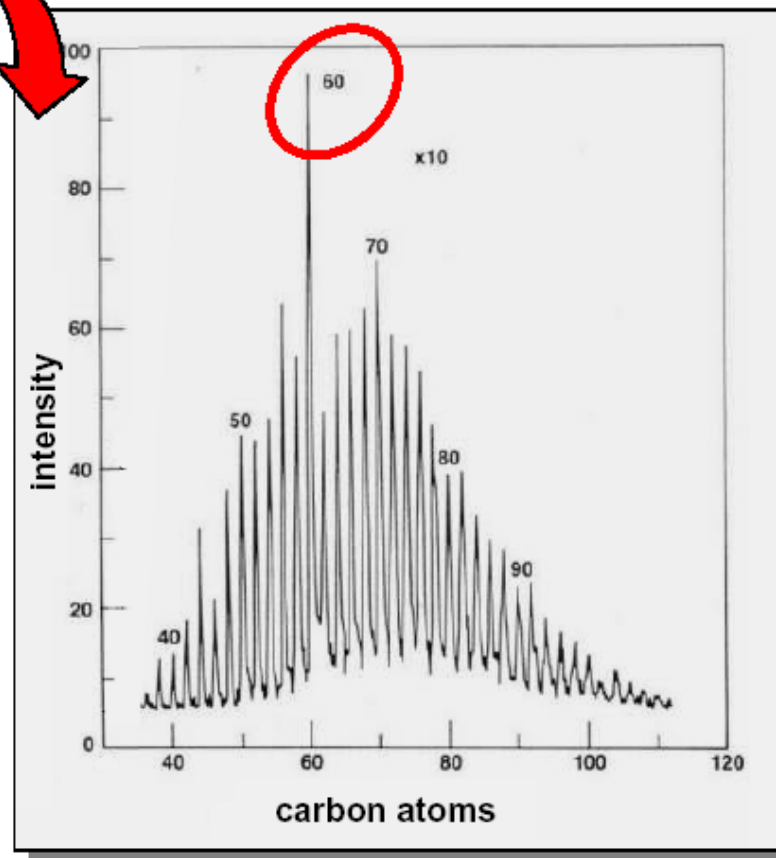


# COMPOSTI AROMATICI POLICICLICI

## Fullerene: la scoperta



$M^+ = 720$



*Nature* **1985**, 318, 162

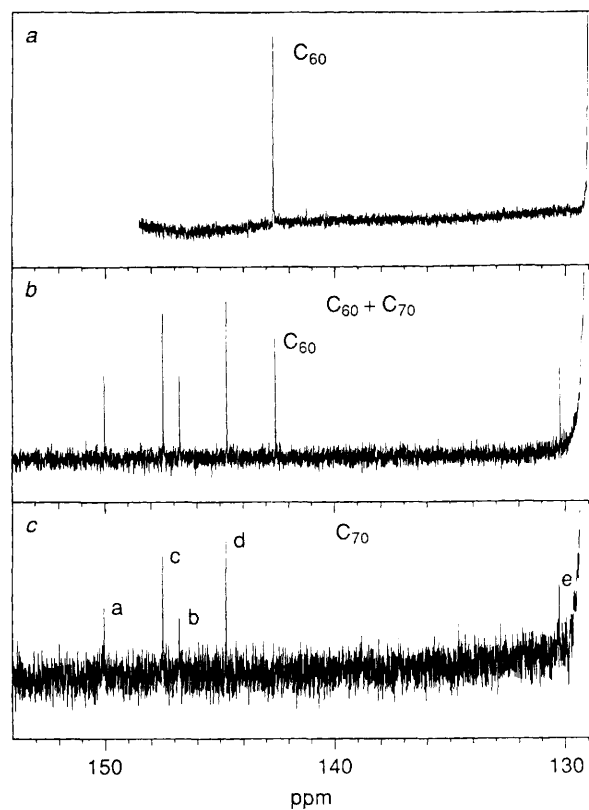
Kroto, Curl, and Smalley  
Nobel, 1996

## Isolation, Separation and Characterisation of the Fullerenes $C_{60}$ and $C_{70}$ : The Third Form of Carbon

Roger Taylor, Jonathan P. Hare, Ala'a K. Abdul-Sada and Harold W. Kroto

School of Chemistry and Molecular Sciences, University of Sussex, Brighton BN1 9QJ, UK

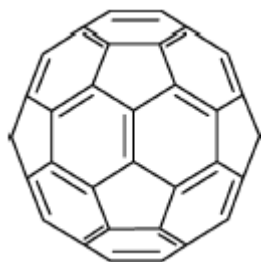
J. CHEM. SOC., CHEM. COMMUN., 1990 1423



**Fig. 3** *a*  $^{13}\text{C}$  NMR spectrum of  $C_{60}$ , Buckminsterfullerene. *b*  $^{13}\text{C}$  NMR spectrum of a mixed sample in which  $C_{60}$  is much reduced. *c*  $^{13}\text{C}$  NMR spectrum of  $C_{70}$ , fullerene-70. The line assignments given are based on the observed intensities and semi-quantitative strain arguments, and are subject to confirmation. The wing of the intense benzene solvent signal lies at the far right hand side

## COMPOSTI AROMATICI POLICICLICI

---



**C<sub>60</sub>**

scoperto nel 1985 da Kroto, Smalley and Curl, *Nature* **1985**, 318, 162

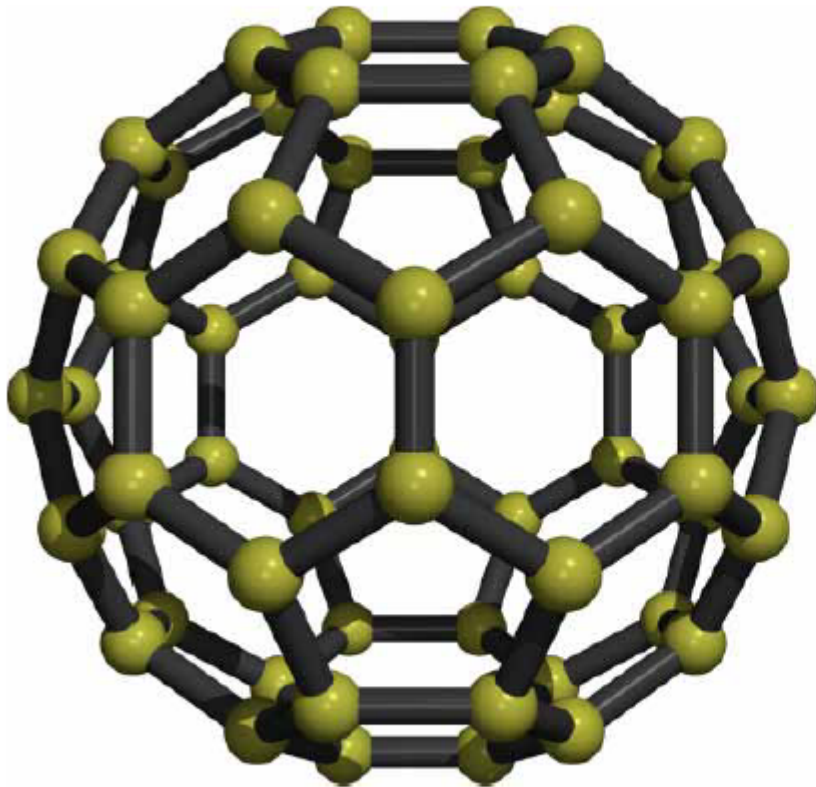
**1996** Chemistry Nobel Prize

**ROBERT F. CURL, Jr. , SIR HAROLD W. KROTO , and RICHARD E. SMALLEY**

"for their discovery of fullerenes"

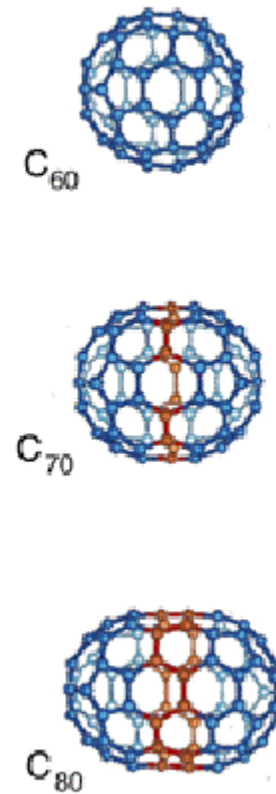
# COMPOSTI AROMATICI POLICICLICI

## Fullereni



Buckminsterfullerene (C<sub>60</sub>)

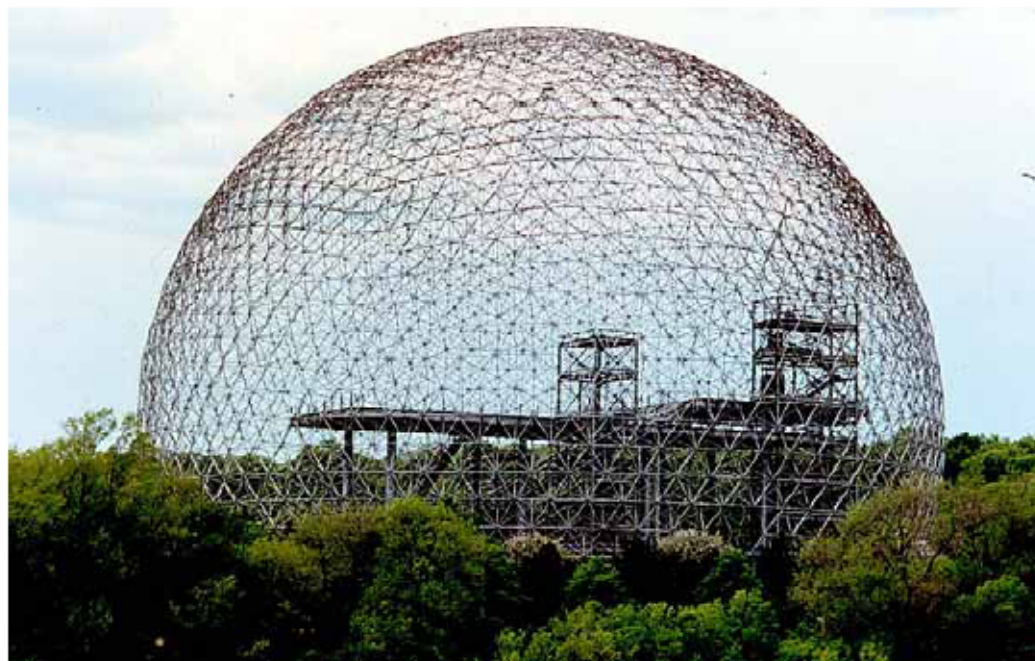
truncated icosahedron (I<sub>h</sub> symmetry)



## COMPOSTI AROMATICI POLICICLICI

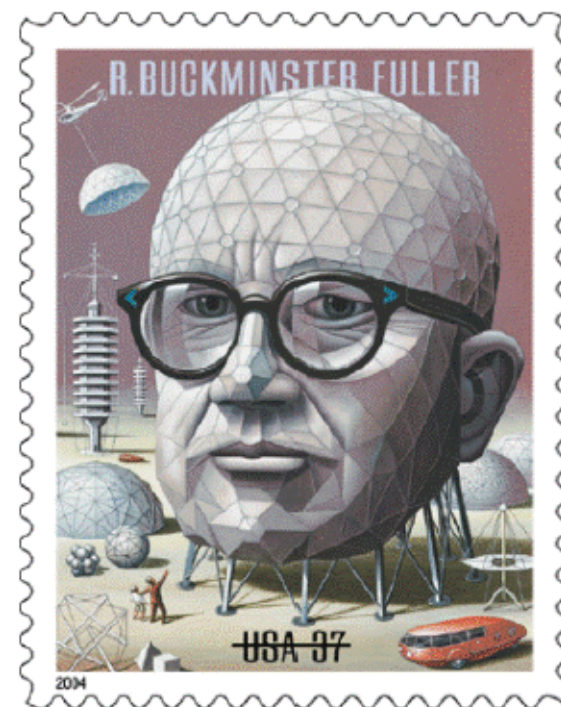
---

# Buckminster Fuller



**Geodesic Dome**

Buckminster Fuller, US Pavilion for the 1967 International and Universal Exposition in Montreal



# COMPOSTI AROMATICI POLICICLICI

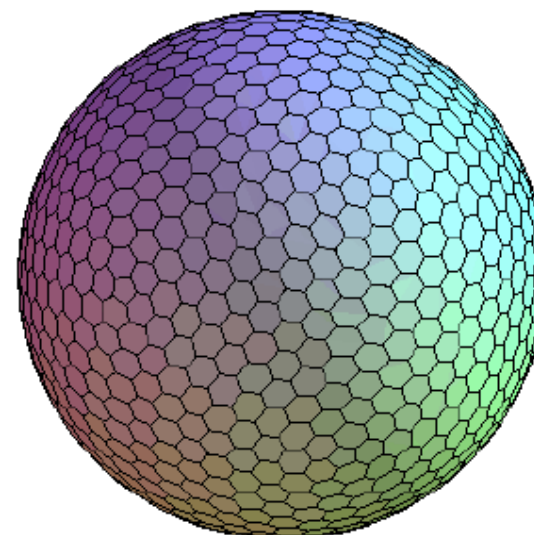
## Regola di Eulero

Un fullerene è un poliedro convesso con  
facce esagonali e pentagonali.

$$F - S + V = 2$$

Se uso solo esagoni  $F - S + V = 0$ . Affinché la  
formula di Eulero per i poliedri sia rispettata,  
occorre che diventi uguale a 2. In breve, occorre  
sostituire **12** esagoni con altrettanti **pentagoni**

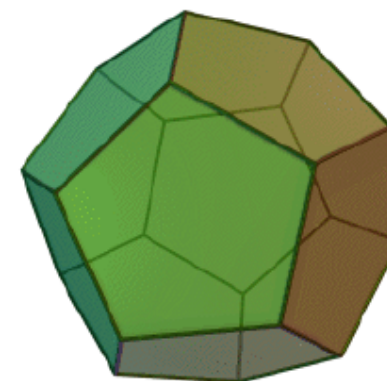
**Il fullerene presenta 20 esagoni  
e 12 pentagoni**



Facce 12

Spigoli 30

Vertici 20



## COMPOSTI AROMATICI POLICICLICI

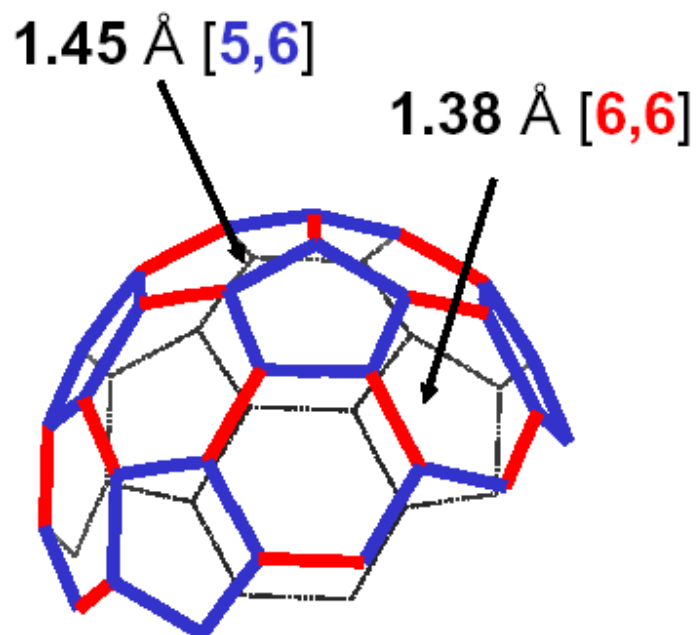
---

### C<sub>60</sub>

- C<sub>60</sub> was found to become a **superconductor** in M<sub>3</sub>C<sub>60</sub> species (M=alkali metal)
- organic soft **ferromagnet** in TDAE<sup>+</sup>C<sub>60</sub><sup>-</sup> (TDAE=tetrakisdimethylaminoethylene) at 16.1 Kelvin
- a relatively stable **hexaanion** in cyclic voltammetry
- an interesting material with **non-linear optical properties**.
  - The C<sub>60</sub> surface contains 20 hexagons and 12 pentagons. All the rings are fused, all the double bonds are conjugated.
- X-Ray crystal structure determinations on C<sub>60</sub> and on some of its derivatives have proved the existence of two different types of bonds: 'short bonds' or 6,6 junctions shared by two adjacent hexagons (ca. 1.38 Å long) and 'long bonds', or 5,6 junctions, fusing a pentagon and a hexagon (ca. 1.45 Å long).

## COMPOSTI AROMATICI POLICICLICI

### Proprietà strutturali del C<sub>60</sub>



$\Delta H_f = 10.16$  Kcal/mol per C  
( $\Delta H_f$ )graphite = 0 Kcal/mol  
( $\Delta H_f$ )diamond = 0.4 Kcal/mol

The six-membered rings are **not aromatic** in that they contain alternating single and double bonds. 6,6-bonds are shorter than 5,6-bonds.

The overall buckyball structure has to be viewed as fused **1,3,5-cyclohexatrienes** and **[5]radialenes**

spherical geometry causes **pyramidalization** of the unsaturated C-atoms. Strain Energy  $\approx 80\%$   $H_f$

- Haddon and Raghavachari, in *buckminsterfullerenes*, VCH, 1993  
- H.D. Beckhaus et al. *Angew. Chem.* 1992, 31, 63)

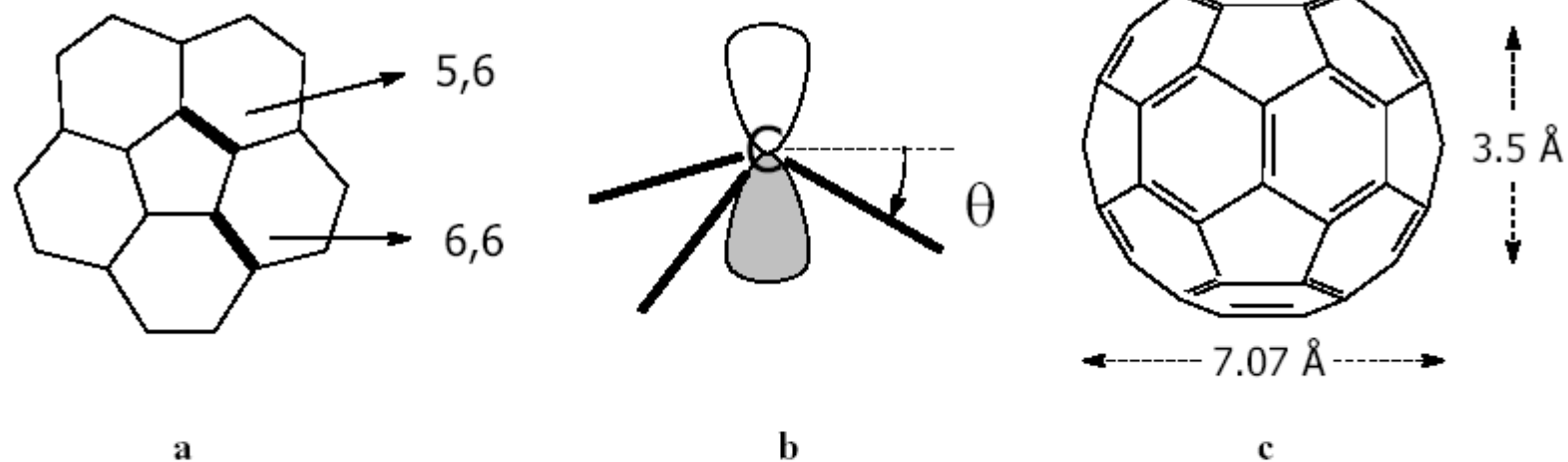
- A. Hirsch, Z. Chen, H. Jiao. *Angew. Chem.* **2000**, 39, 3915.

- M. Bühl, A. Hirsch *Chem. Rev.* **2001**, 101, 1119.



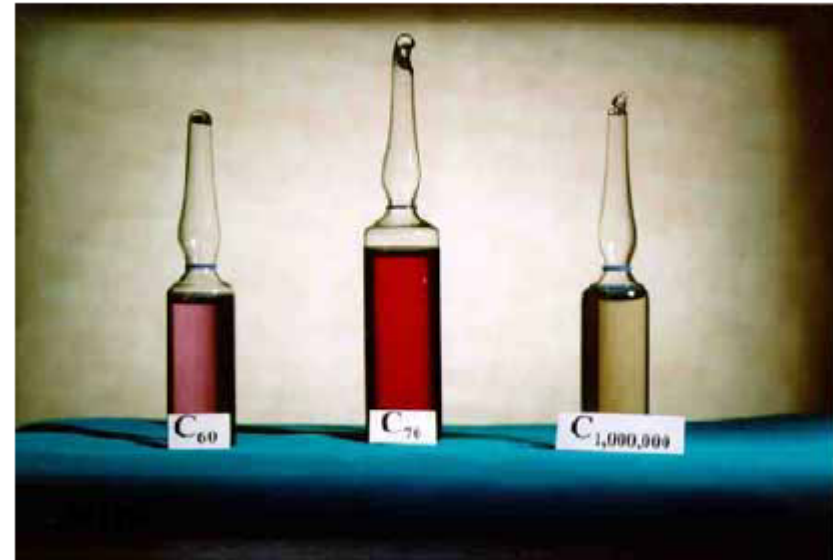
## COMPOSTI AROMATICI POLICICLICI

### Proprietà strutturali del $C_{60}$

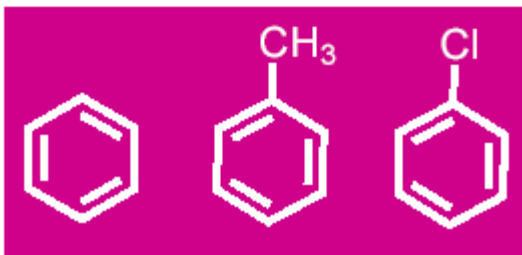


(a) legami 5,6 e 6,6 nel  $C_{60}$ ; (b) angolo di piramidalizzazione  $\theta$ ; (c) diametro esterno (*edge-to-edge*) e interno del  $C_{60}$  (il diametro di Wan der Waals è circa 10.4 Å)

# COMPOSTI AROMATICI POLICICLICI



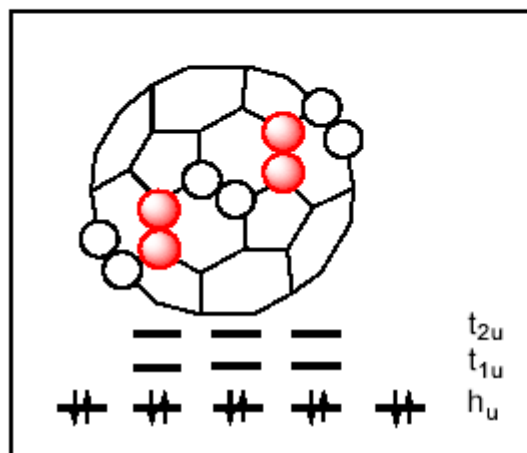
**C<sub>60</sub> solution in toluene**



and CS<sub>2</sub>

# COMPOSTI AROMATICI POLICICLICI

## Reattività



C<sub>60</sub> behaves essentially as a **strained electron-poor alkene**; addition chemistry is mainly driven by strain relief

fullerenes are very difficult to oxidize but are **readily reduced** (reactivity towards electron-rich reagents)

**1,2-additions** occur at 6,6-double bonds. In 1,2-adducts the bond-length alternation is totally preserved

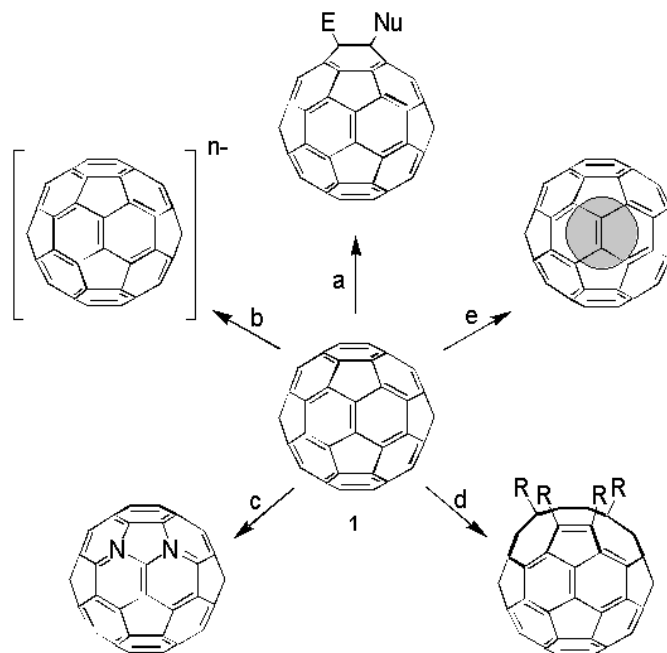
the regioselectivity of addition reactions is governed by **avoidance of products with 5,6 double bonds** in the lowest energy Kekulé structure (price tag of 8.5 kcal mol<sup>-1</sup>)

multiple addition to C<sub>60</sub> is a complicated process governed by differences in bond order and LUMO coefficients at each site: many possible **regio-isomers**

# COMPOSTI AROMATICI POLICICLICI

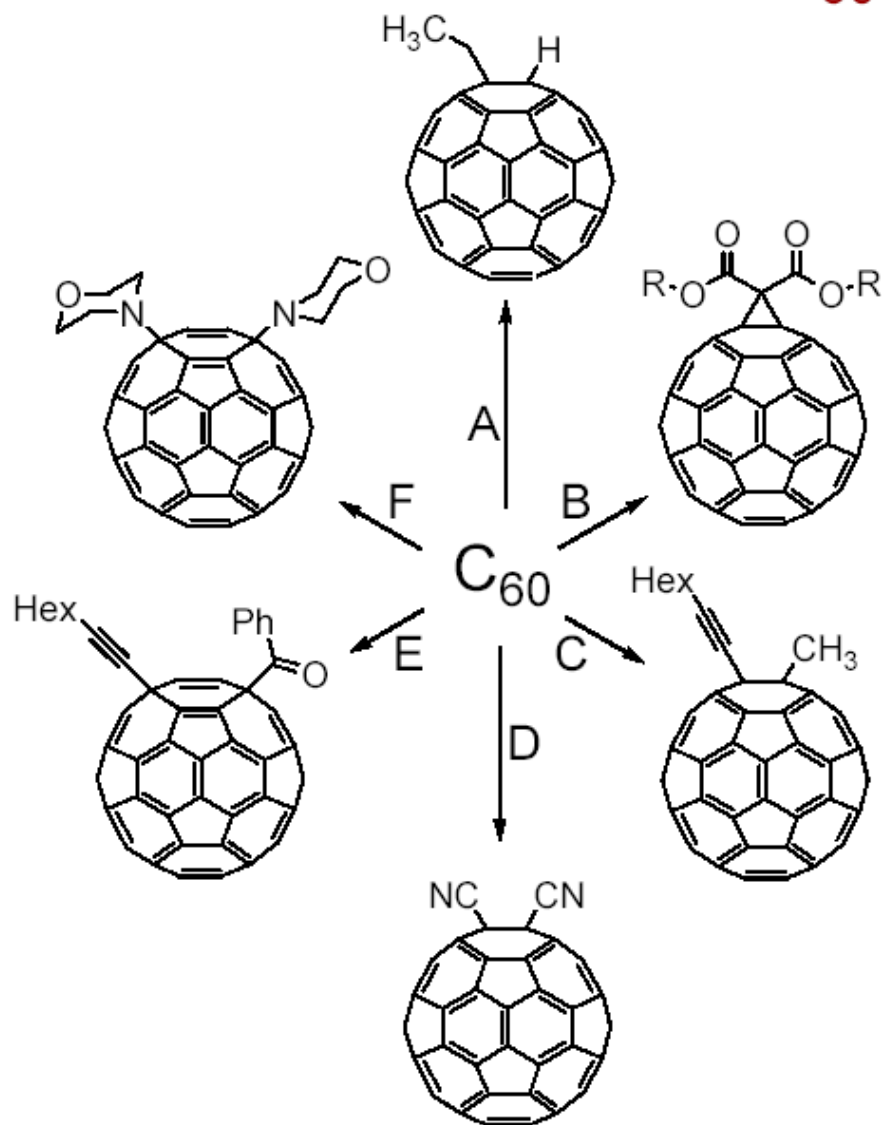
The **chemical transformations** that are possible with C<sub>60</sub> could be classified in five main groups (figure 1.3):

- Addition reactions.* Formation of exohedral compounds by addition of nucleophiles or radicals, cycloadditions, complexations with transition metals and others.
- Electron transfer reactions.* Chemical reduction of fullerenes can easily be achieved by reaction with electropositive alkali and alkaline earth metals or organic donor molecules.
- Heterofullerenes.* Substitution of a carbon atom of the fullerene skeleton for a heteroatom, for example nitrogen or boron.
- Ring opening reactions.* Producing a hole in the C<sub>60</sub> skeleton while breaking a discrete number of bonds.
- Formation of endohedrals.* Introducing and trapping of atoms inside the spherical carbon cage.

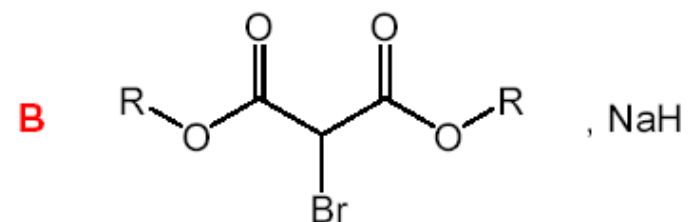


# COMPOSTI AROMATICI POLICICLICI

## Addizioni nucleofile al $C_{60}$



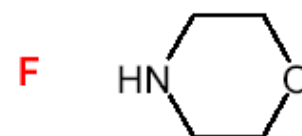
**A** EtMgBr,  $H^+$



**C** Hex— $\equiv$ Li , MeI

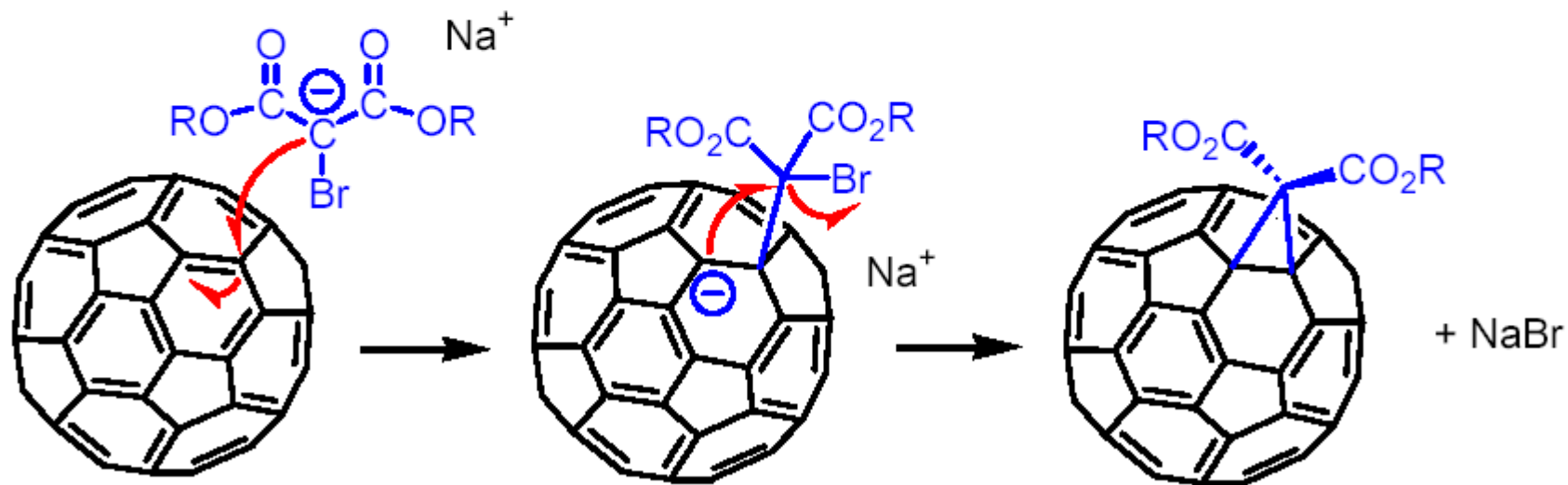
**D** NaCN, TsCN

**E** Hex— $\equiv$ Li , PhCOCl



## COMPOSTI AROMATICI POLICICLICI

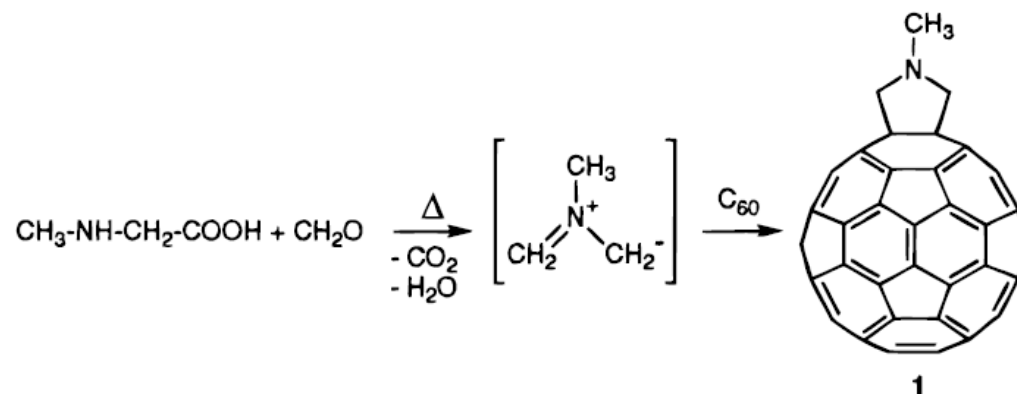
### Ciclopropanazione del $C_{60}$ (metanofullereni)



## COMPOSTI AROMATICI POLICICLICI

### 1,3-dipolar cycloaddition of azomethine ylides to C<sub>60</sub>

the Prato's reaction



41% yield

82% on the consumed C<sub>60</sub>

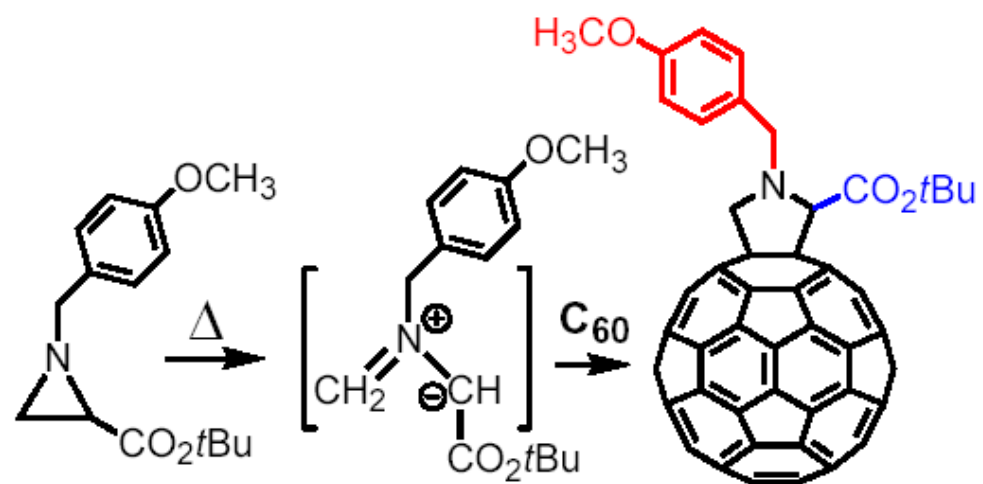
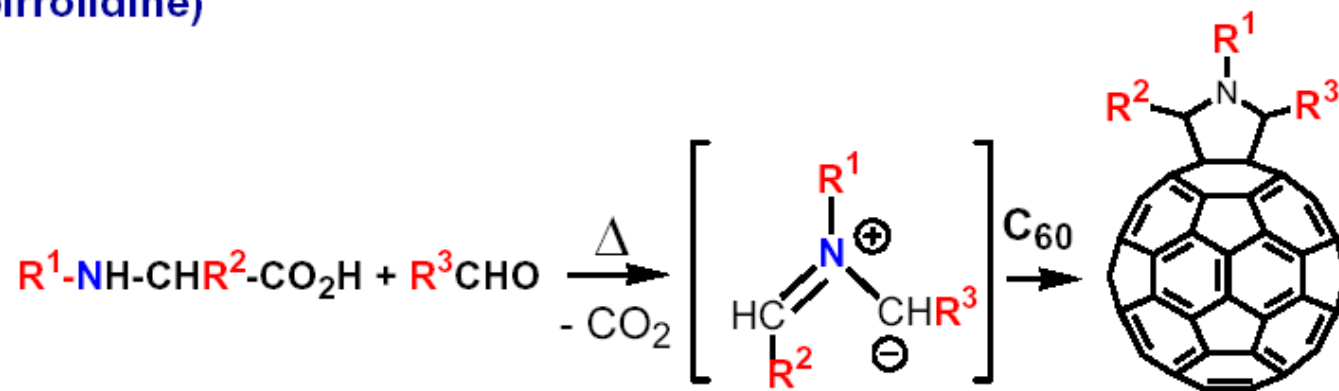
the reaction is site selective in that it affords exclusively the product of cycloaddition across a 6,6 ring junction of the fullerene

Maggini, M.; Scorrano, G.; Prato, M. *J. Am. Chem. Soc.* **1993**, *115*, 9798–9799.

## COMPOSTI AROMATICI POLICICLICI

### Cicloaddizione di ilidi azometiniche

(fulleropirrolidine)



M. Maggini, G. Scorrano, M. Prato *J. Am. Chem. Soc.* **1993**, 9798

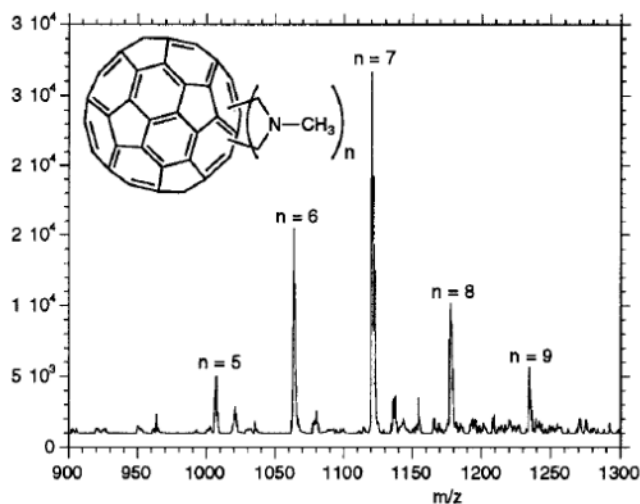
M. Prato, M. Maggini *Acc. Chem. Res.* **1998**, 519

X. Zhang, M. Willems, C. S. Foote *Tetrahedron Lett.* **1993**, 8187



# COMPOSTI AROMATICI POLICICLICI

In the presence of large excesses of reagents, up to nine pyrrolidine rings can be introduced, as detected by MS analysis of the reaction crude.



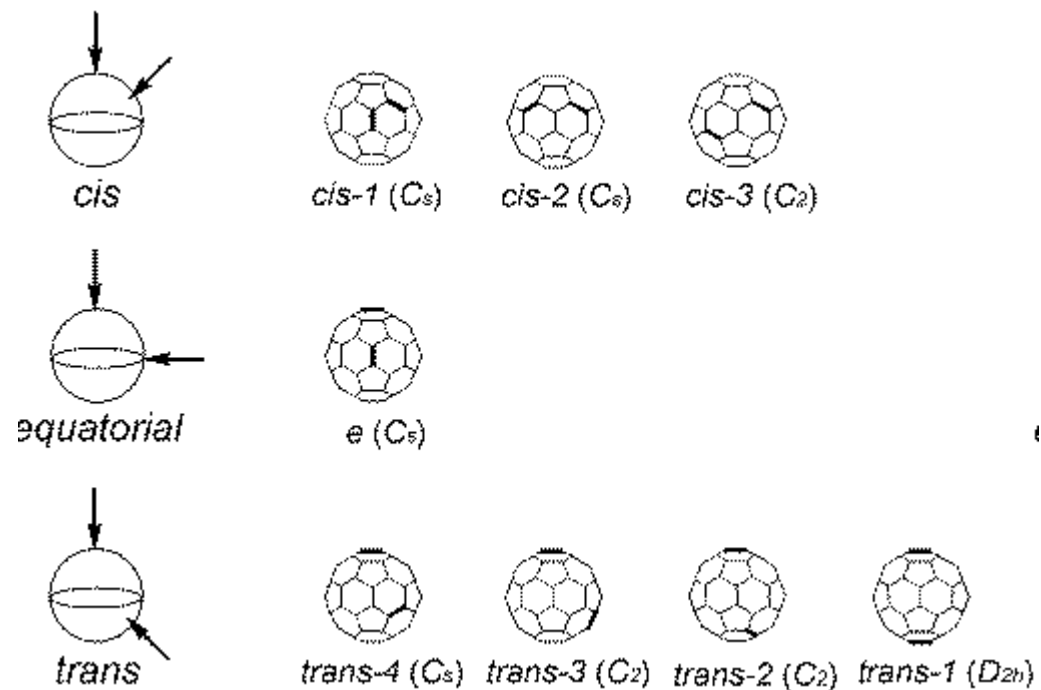
**FIGURE 1.** APCI-MS spectrum of the crude mixture obtained by heating a toluene solution containing C<sub>60</sub>, 20 equiv of sarcosine, and 20 equiv of formaldehyde for 8 h.

Maggini, M.; Scorrano, G.; Prato, M. *J. Am. Chem. Soc.* **1993**, *115*, 9798–9799.

# COMPOSTI AROMATICI POLICICLICI

---

## C60 bis-adducts



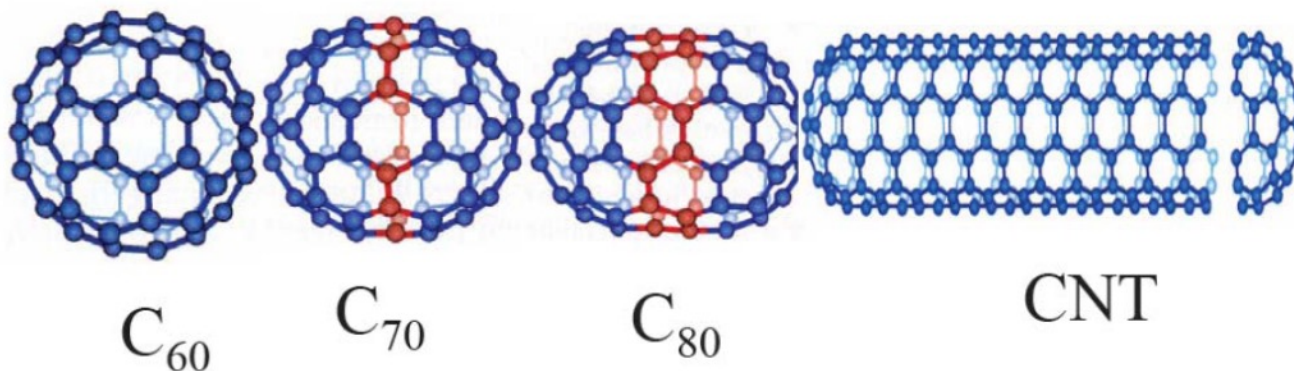
## COMPOSTI AROMATICI POLICICLICI

---

### CNTs discover

A paper by Oberlin, Endo, and Koyama published in **1976** clearly showed hollow carbon fibers with nanometer-scale diameters using a vapor-growth technique (Oberlin, A.; M. Endo, and T. Koyama, *J. Cryst. Growth* (March 1976). *Filamentous growth of carbon through benzene decomposition*. **32**. pp. 335–349.)

Iijima, Sumio (**1991**). "Helical microtubules of graphitic carbon".  
*Nature* **354**: 56–58.

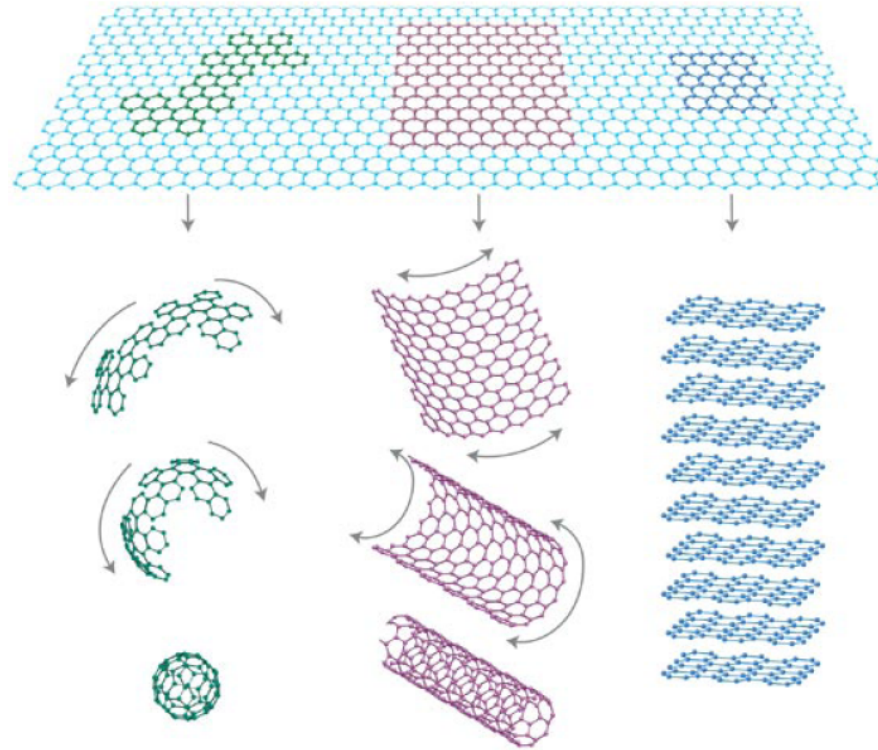


# COMPOSTI AROMATICI POLICICLICI

---

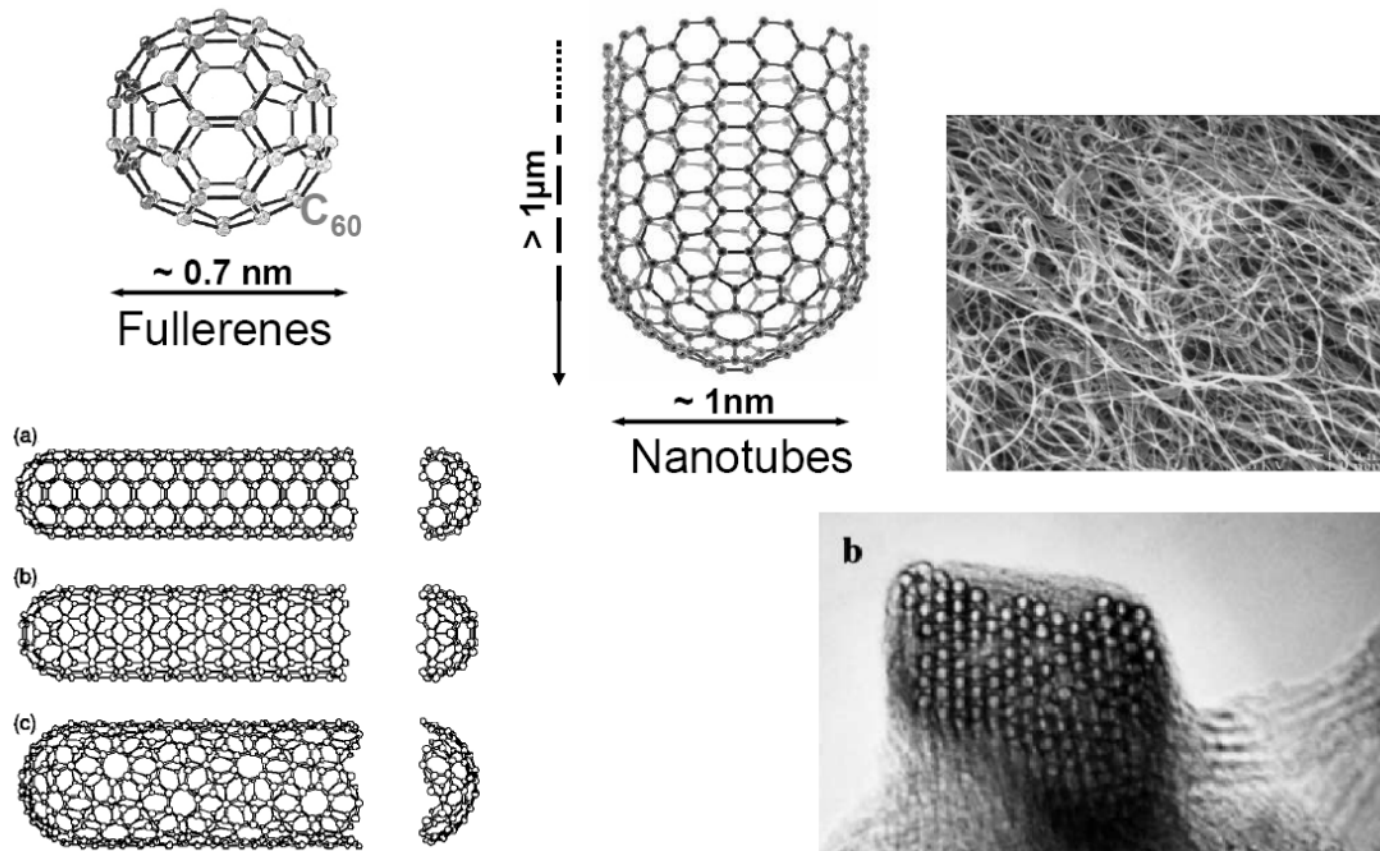
## graphene

the mother of all carbon nanostructures



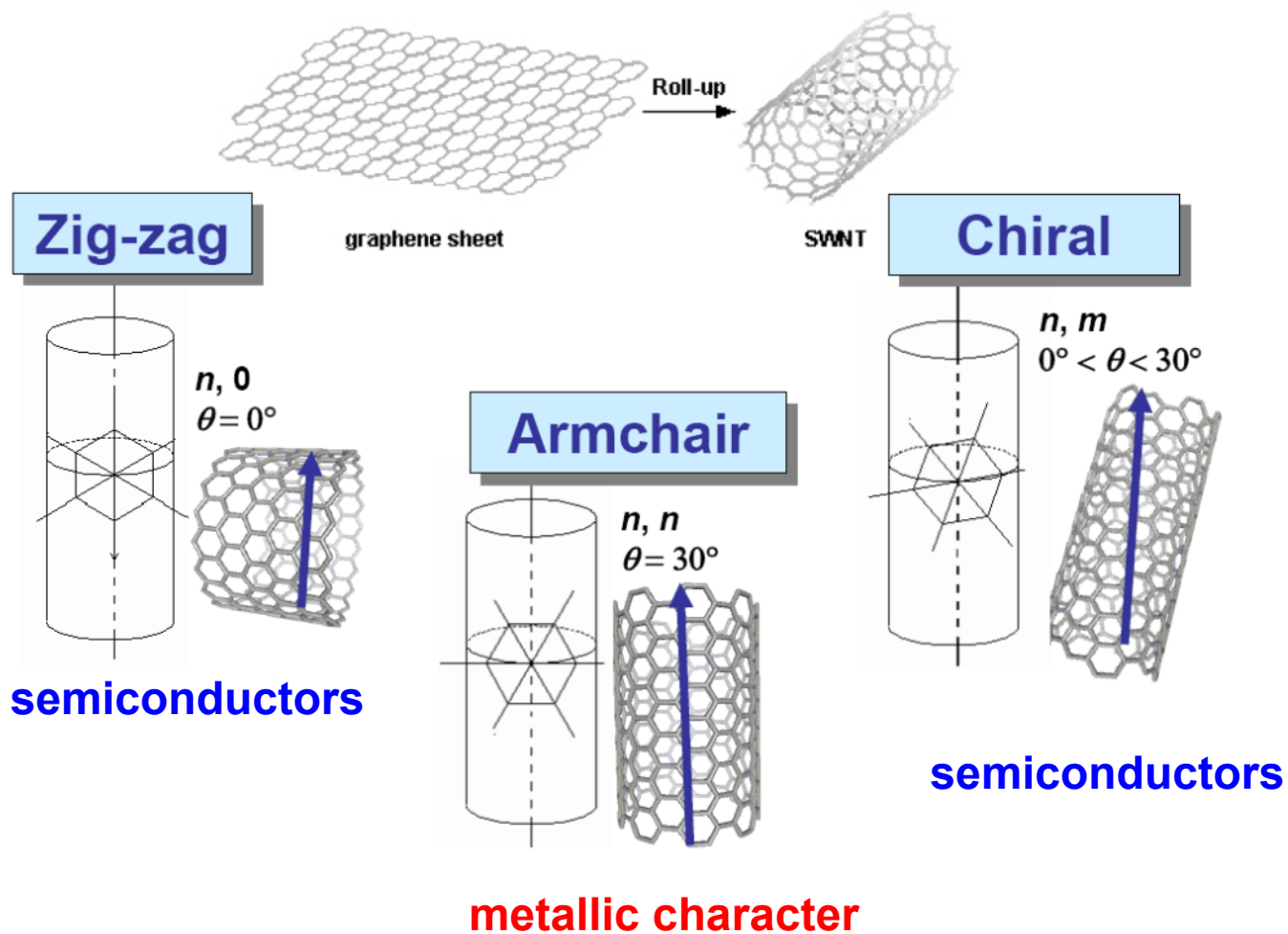
# COMPOSTI AROMATICI POLICICLICI

## nanotubes



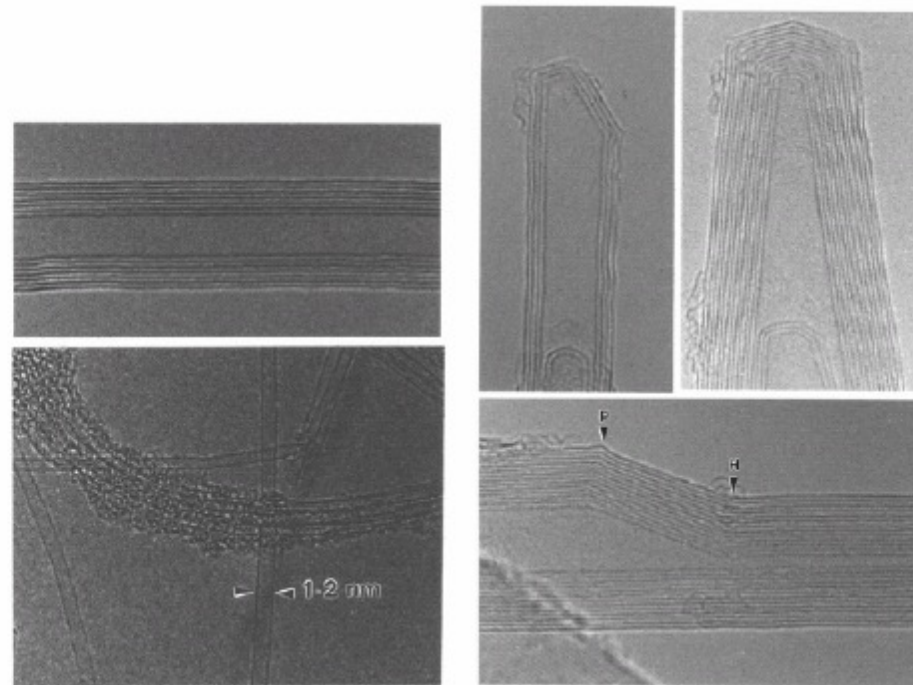
# COMPOSTI AROMATICI POLICICLICI

## structure



## COMPOSTI AROMATICI POLICICLICI

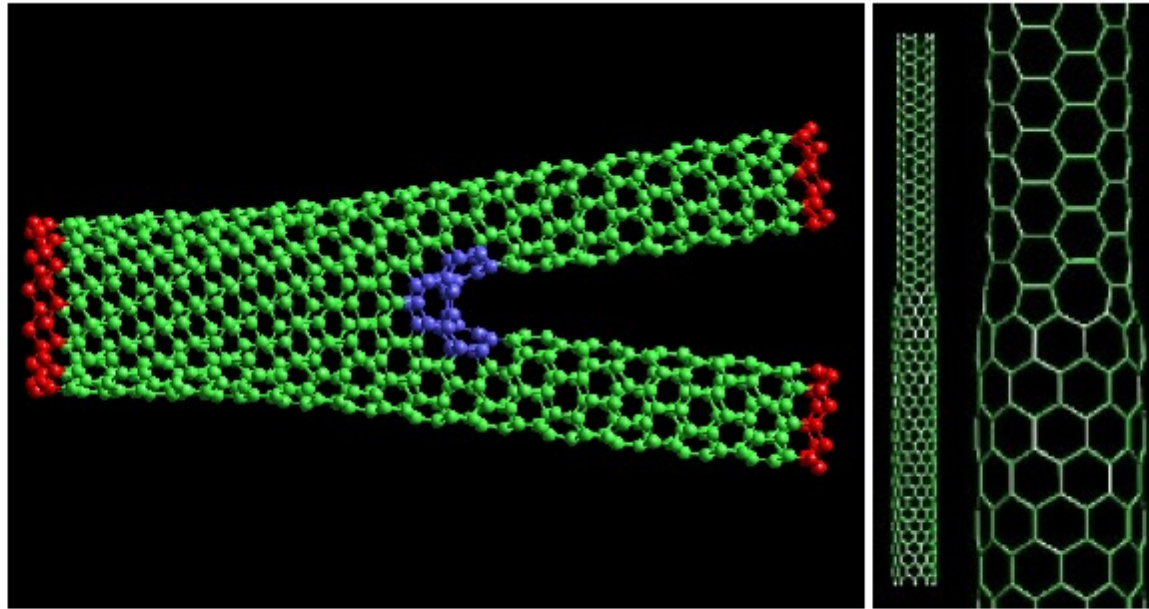
---



*Figure 1-4: Different structures of MWNTs. Top-left: cross-section of a MWNT the different walls are obvious, they are separated by 0.34nm. Rotation around the symmetry axis gives us the MWNT. Top-right: Symmetrical or non-symmetrical cone shaped end caps of MWNTs. Bottom-left: A SWNT with a diameter of 1,2nm and a bundle of SWNTs covered with amorphous carbon. Bottom-right: A MWNT with defects. In point P a pentagon defect and in point H a heptagon defect.<sup>6</sup>*

## COMPOSTI AROMATICI POLICICLICI

---



*Figure 1-5: Left: A Y-branch, the defects are marked in blue. Right: A transition from a metallic to a semi-conducting SWNT. The change is made by insertion of pentagons and heptagons.*



# CNTs properties

SWNTs with different chiral vectors have dissimilar properties such as optical activity, mechanical, strength and electrical conductivity.

CNTs are 100 times stronger than steel

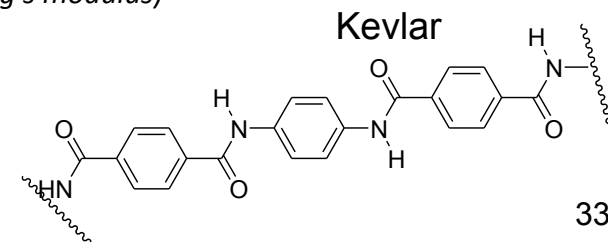
Comparison of Mechanical Properties

Material	Young's Modulus(1) (GPa)	Tensile Strength (GPa)	Elongation at Break (%)
SWNT	~1 (from 1 to 5)	13-53 <sup>E</sup>	16
Armchair SWNT	0.94 <sup>T</sup>	126.2 <sup>T</sup>	23.1
Zigzag SWNT	0.94 <sup>T</sup>	94.5 <sup>T</sup>	15.6-17.5
Chiral SWNT	0.92		
MWNT	0.8-0.9 <sup>E</sup>	150	
Stainless Steel	~0.2	~0.65-1	15-50
Kevlar	~0.15	~3.5	~2
Kevlar <sup>T</sup>	0.25	29.6	

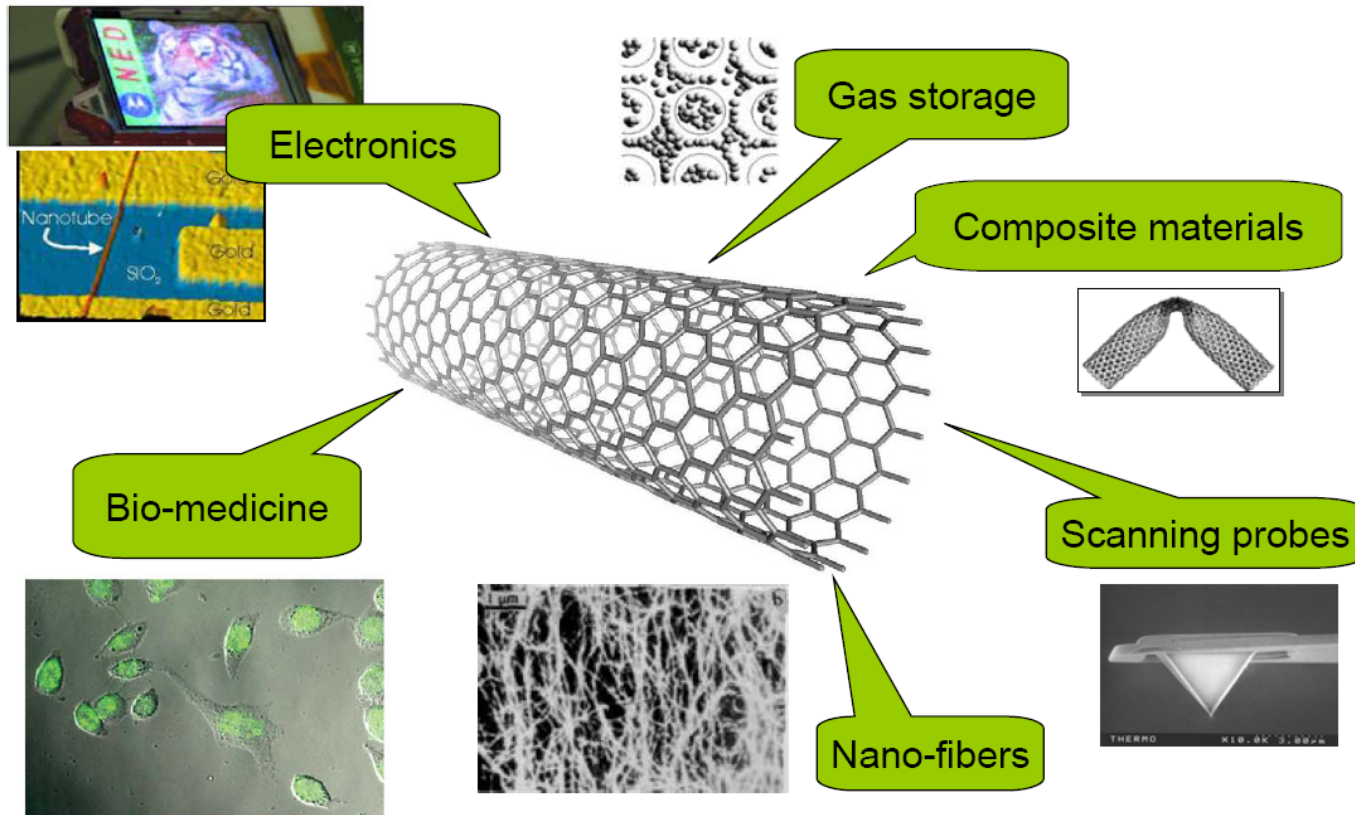
1. misura della durezza di un materiale elastico

(The tangent modulus of the initial, linear portion of a stress-strain curve is called *Young's modulus*)

around \$1500 per gram as of 2000  
 ~\$50–100 per gram as of 2007



# COMPOSTI AROMATICI POLICICLICI



I CNT sono meccanicamente molto più resistenti delle tradizionali fibre di carbonio (sono 100 volte più forti dell'acciaio, 2 volte più leggeri dell'alluminio) ed eccezionalmente flessibili quando assoggettati a distorsioni (possono essere piegati a grandi angoli e poi raddrizzati senza danno).

# COMPOSTI AROMATICI POLICICLICI

## purification

### Oxidation

- acid solution

- air at high T

### Separation

- surfactants

- chromatography

### Annealing

10.5 %

1 %



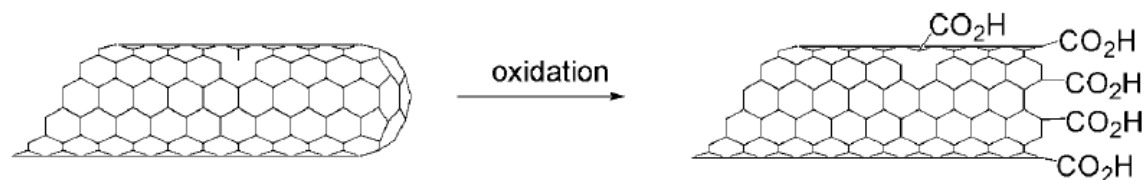
C. Furtado et al., *J. Am. Chem. Soc.* **2004**, *126*, 6095-6105

R. C. Haddon et al., *Mrs Bulletin* **2004**, *29*, 252-259.

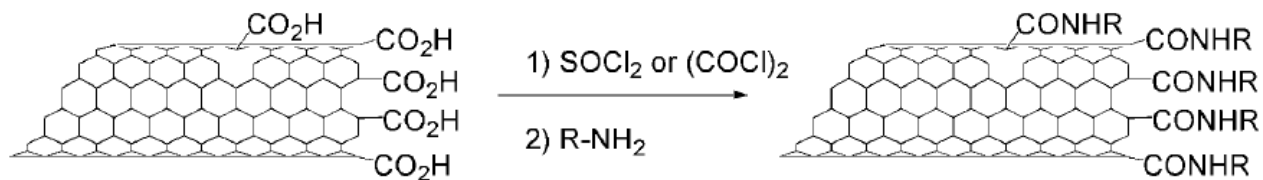
# COMPOSTI AROMATICI POLICICLICI

## funzionalizzazione di CNT

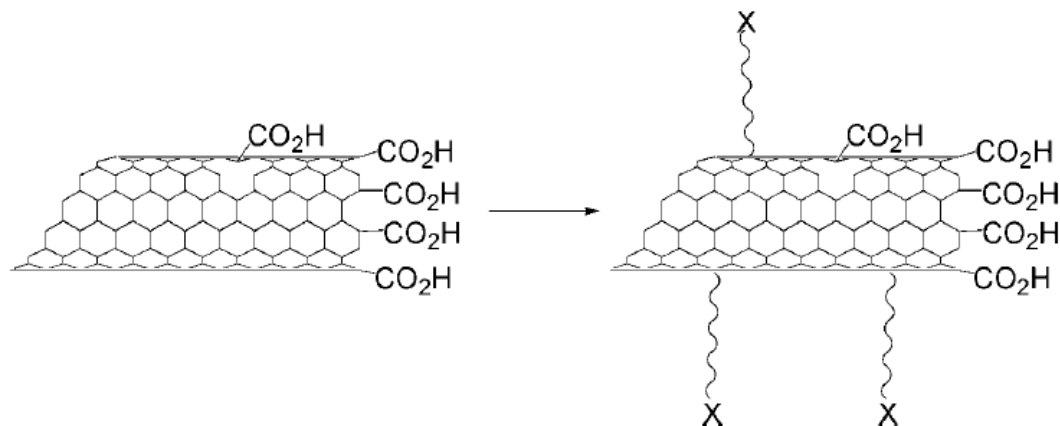
SCHEME 2. Oxidation of Carbon Nanotubes



SCHEME 3. Amidation Reaction of Oxidized Carbon Nanotubes



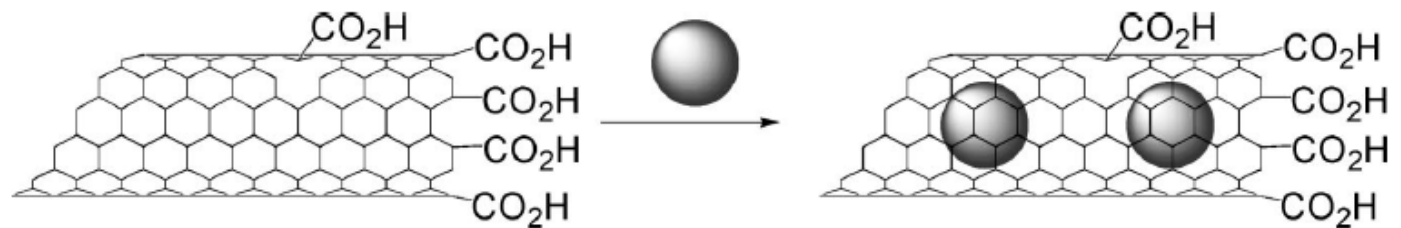
SCHEME 4. Functionalization of Carbon Nanotubes Using Addition Reactions (X = Functional Groups)



# COMPOSTI AROMATICI POLICICLICI

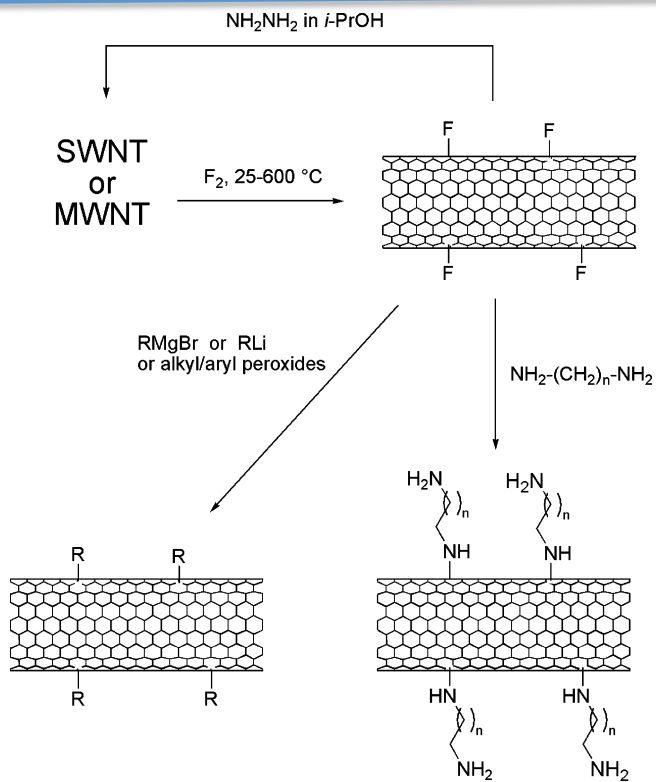
---

**SCHEME 5.** Insertion inside Carbon Nanotubes

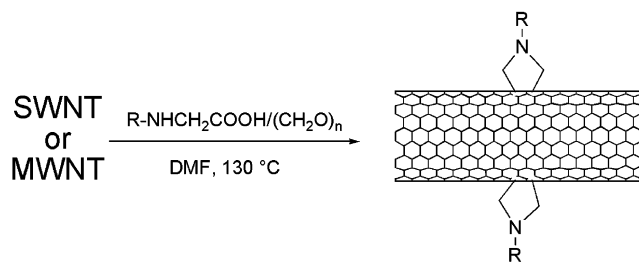


fullerenes, porphyrins, and metals, have indeed been included in the internal space of CNT, mostly due to hydrophobic interactions

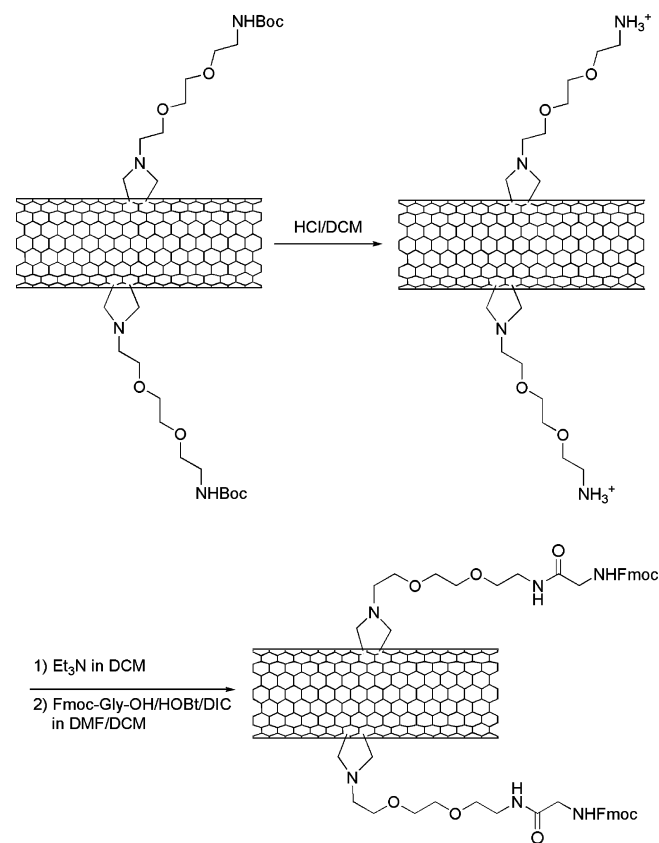
# COMPOSTI AROMATICI POLICICLICI



**Figure 1.** Reaction scheme for fluorination of nanotubes, defunctionalization, and further derivatization.

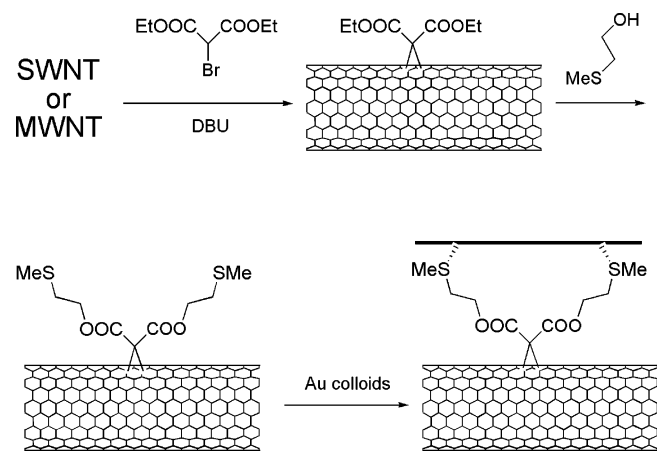


**Figure 5.** 1,3-Dipolar cycloaddition of azomethine ylides.

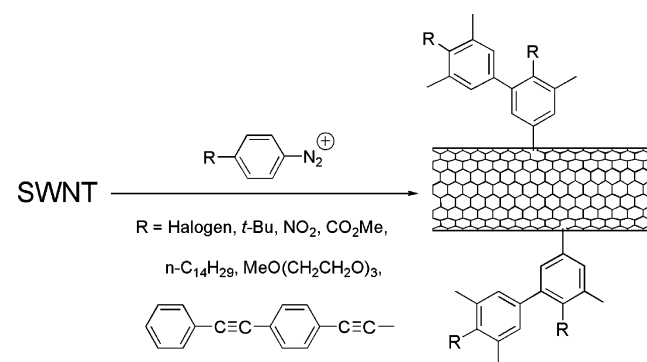


**Figure 6.** Reaction pathway for obtaining water-soluble ammonium-modified nanotubes. The latter can be used for the delivery of biomolecules.

# COMPOSTI AROMATICI POLICICLICI



**Figure 8.** Bingel reaction on nanotubes and subsequent attachment to gold nanoparticles.

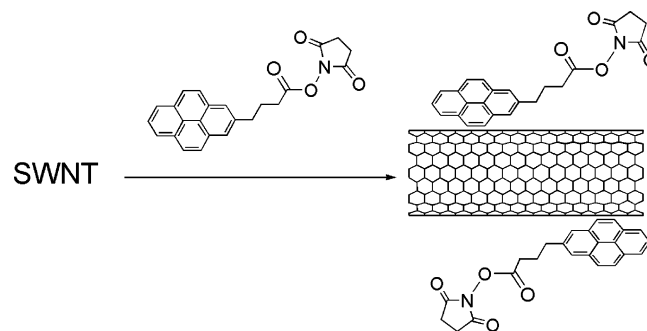


**Figure 9.** Derivatization scheme by reduction of aryl diazonium salts.

# COMPOSTI AROMATICI POLICICLICI

---

funzionalizzazione via interazioni deboli



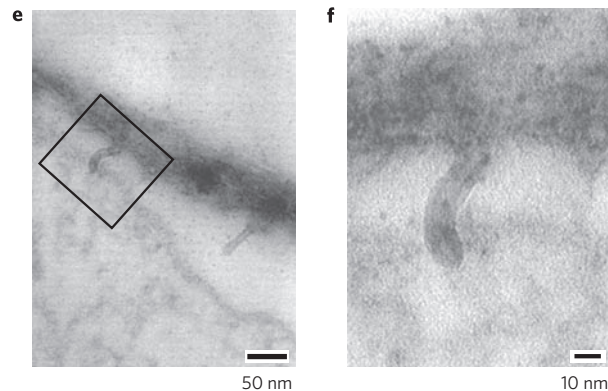
**Figure 19.** Interactions of nanotubes with pyrene derivatives.



## Carbon nanotubes might improve neuronal performance by favouring electrical shortcuts

Giada Cellot<sup>1</sup>, Emanuele Cilia<sup>1†</sup>, Sara Cipollone<sup>2</sup>, Vladimir Rancic<sup>1</sup>, Antonella Sucapane<sup>1</sup>, Silvia Giordani<sup>2†</sup>, Luca Gambazzi<sup>3</sup>, Henry Markram<sup>3</sup>, Micaela Grandolfo<sup>4</sup>, Denis Scaini<sup>5</sup>, Fabrizio Gelain<sup>6</sup>, Loredana Casalis<sup>5</sup>, Maurizio Prato<sup>2</sup>, Michele Giugliano<sup>3,7\*</sup> and Laura Ballerini<sup>1\*†</sup>

we show, using single-cell electrophysiology techniques, electron microscopy analysis and theoretical modelling, that nanotubes improve the responsiveness of neurons by forming tight contacts with the cell membranes that might favour electrical shortcuts between the proximal and distal compartments of the neuron.

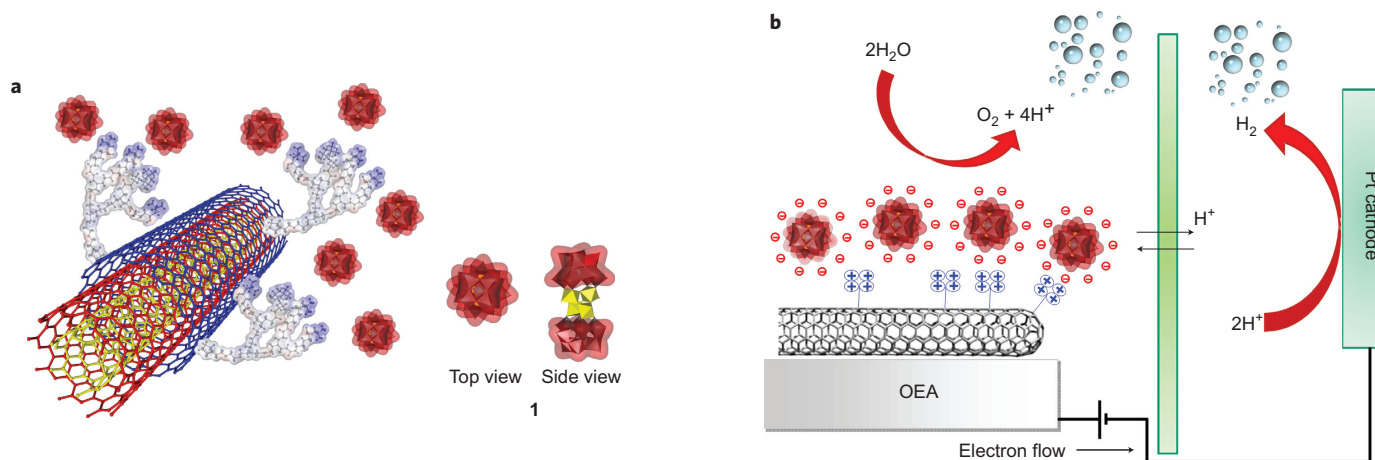


tight contact between nanotubes and membranes. The morphology of such contacts is indicative of the development of hybrid nanotubes – neuronal units .

High-magnification micrographs from a section consecutive to those of b and c. The rectangular area in e is magnified in f. Note how nanotubes are 'pinching' neuronal membranes.

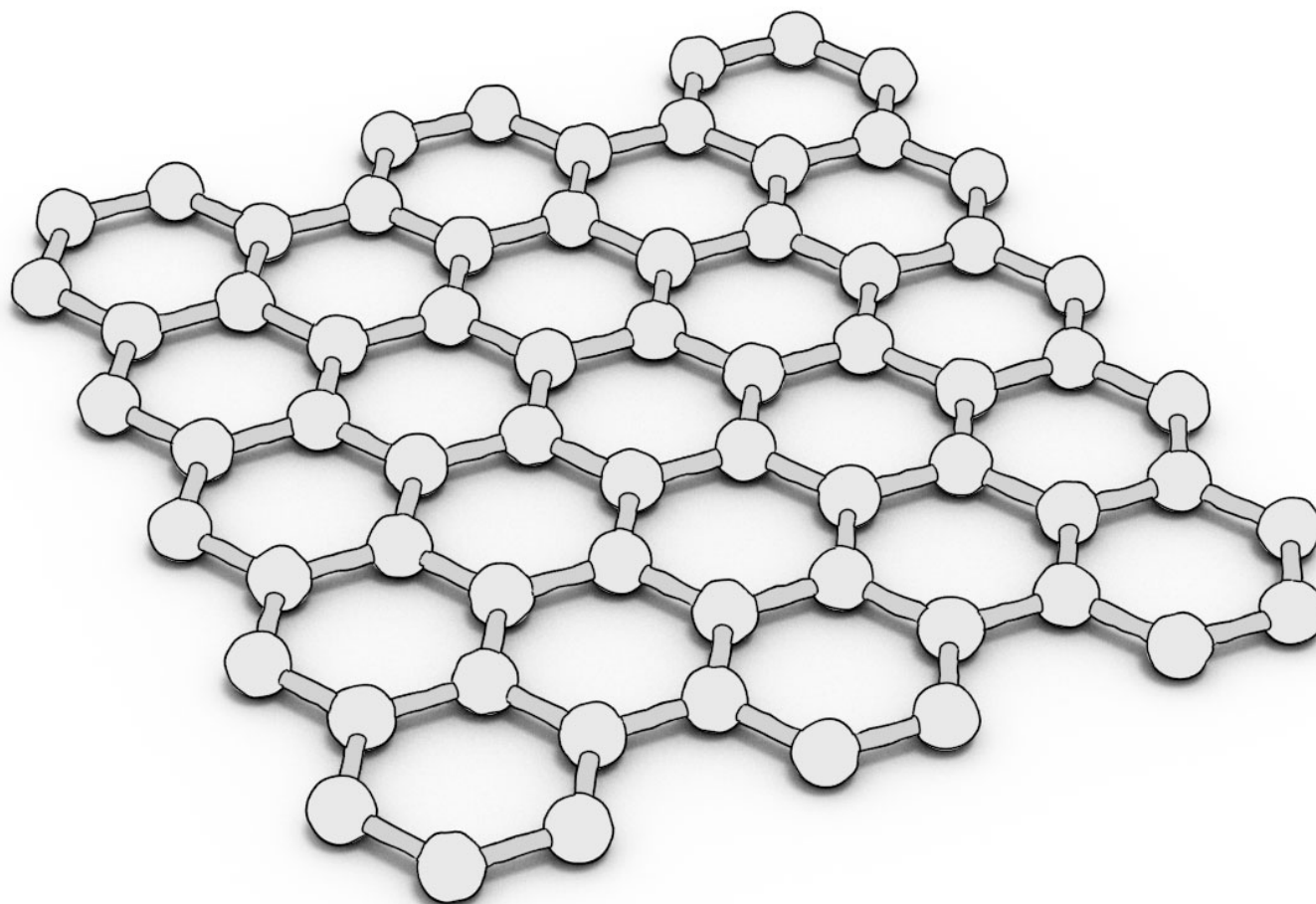
# Efficient water oxidation at carbon nanotube-polyoxometalate electrocatalytic interfaces

Francesca M. Toma<sup>1,2</sup>, Andrea Sartorel<sup>3</sup>, Matteo Iurlo<sup>4</sup>, Mauro Carraro<sup>3</sup>, Pietro Parisse<sup>2,5</sup>, Chiara Maccato<sup>3</sup>, Stefania Rapino<sup>4</sup>, Benito Rodriguez Gonzalez<sup>6</sup>, Heinz Amenitsch<sup>7</sup>, Tatiana Da Ros<sup>1</sup>, Loredana Casalis<sup>2,5</sup>, Andrea Goldoni<sup>5</sup>, Massimo Marcaccio<sup>4</sup>, Gianfranco Scorrano<sup>3</sup>, Giacinto Scoles<sup>2</sup>, Francesco Paolucci<sup>4</sup>, Maurizio Prato<sup>1\*</sup> and Marcella Bonchio<sup>3\*</sup>



**Figure 1 | Nanostructured oxygen-evolving material.** **a**, Electrostatic capture of polyanionic ruthenium-containing clusters **1** (negatively charged, red surface) by polycationic dendrons on the MWCNT surface (positively charged, blue surface) and polyhedric structure showing the side and front view of the POM (red)-embedded tetraruthenate core of **1** (yellow). **b**, General scheme for a water-splitting electrocatalytic cell with the integrated nanostructured OEA.

# Graphene



**Graphene** is an allotrope (form) of carbon consisting of a single layer of carbon atoms arranged in a hexagonal lattice.

It can be considered as an indefinitely large aromatic molecule, the ultimate case of the family of flat polycyclic aromatic hydrocarbons.

The material was rediscovered, isolated, and characterized in **2004** by **Andre Geim** and **Konstantin Novoselov** at the University of Manchester.

This work resulted in the two winning the **Nobel Prize in Physics in 2010** "for groundbreaking experiments regarding the two-dimensional material graphene".

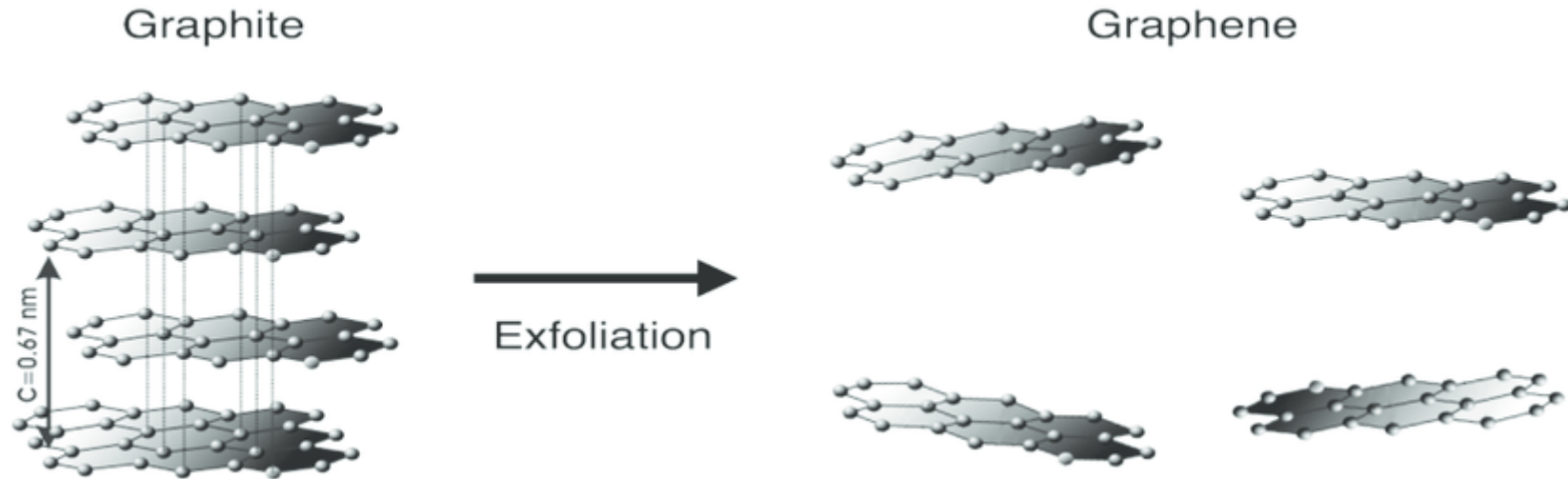


Andre Geim



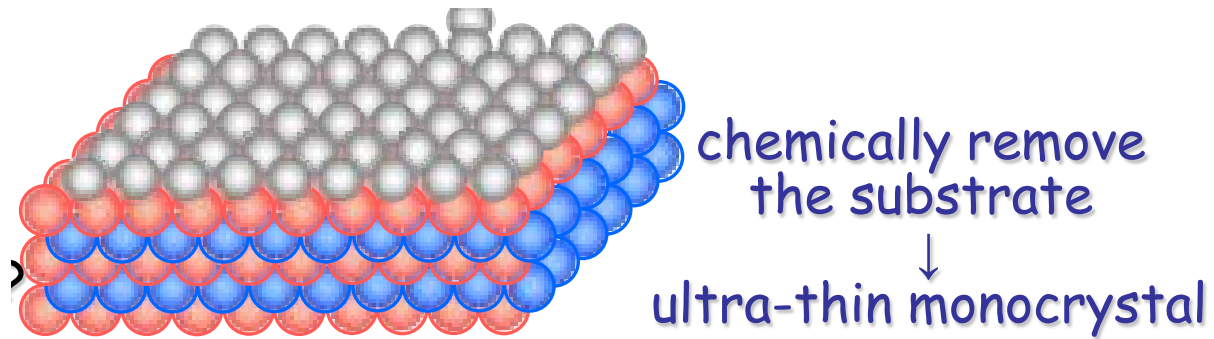
Konstantin Novoselov

## exfoliation



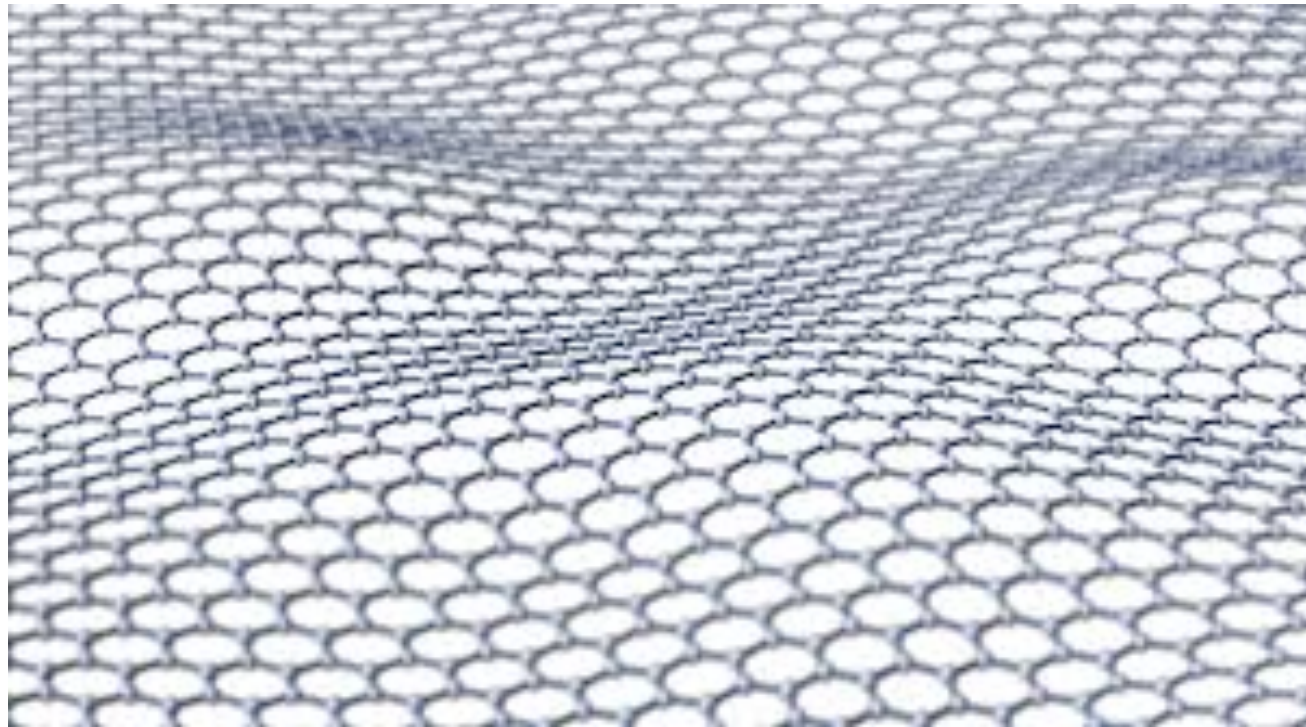
highly oriented pyrolytic graphite (HOPG)

## Epitaxial growth



"Graphene" is a combination of "graphite" and the suffix -ene, named by Hanns-Peter Boehm, who described single-layer carbon foils in 1962.

Graphene can be considered an "infinite alternant" (only six-member carbon ring) polycyclic aromatic hydrocarbon



nanoscale corrugation

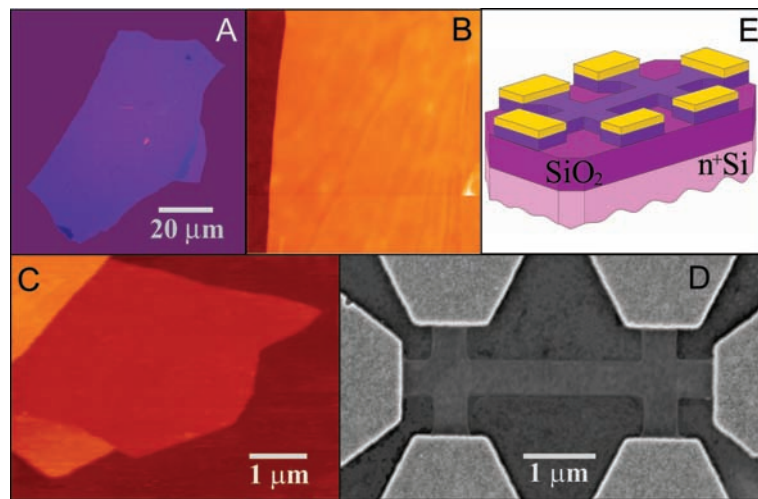
# Electric Field Effect in Atomically Thin Carbon Films

2 OCTOBER 2004 VOL 306 SCIENCE, p. 666

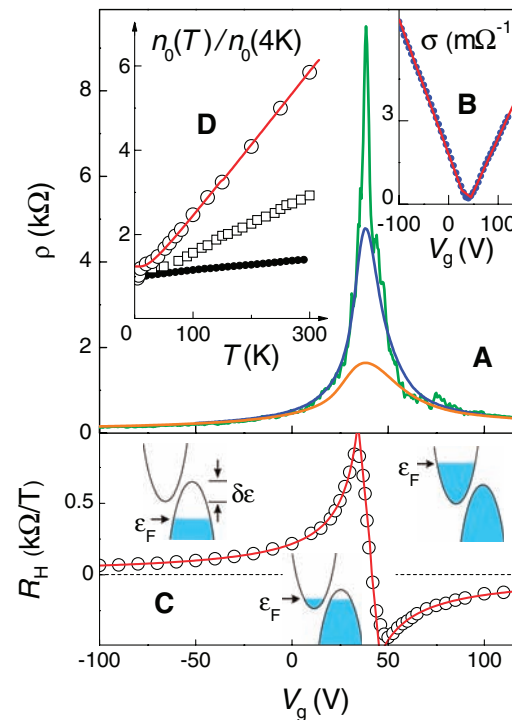
K. S. Novoselov,<sup>1</sup> A. K. Geim,<sup>1\*</sup> S. V. Morozov,<sup>2</sup> D. Jiang,<sup>1</sup>  
 Y. Zhang,<sup>1</sup> S. V. Dubonos,<sup>2</sup> I. V. Grigorieva,<sup>1</sup> A. A. Firsov<sup>2</sup>

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to  $10^{13}$  per square centimeter and with room-temperature mobilities of  $\sim 10,000$  square centimeters per volt-second can be induced by applying gate voltage.

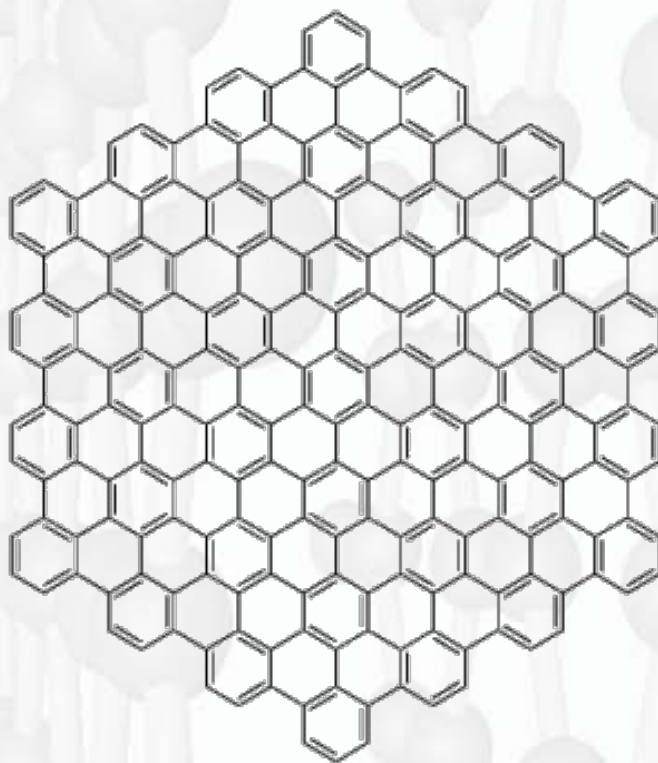
## Field effect



**Fig. 1.** Graphene films. (A) Photograph (in normal white light) of a relatively large multilayer graphene flake with thickness  $\sim 3$  nm on top of an oxidized Si wafer. (B) Atomic force microscope (AFM) image of  $2 \mu\text{m}$  by  $2 \mu\text{m}$  area of this flake near its edge. Colors: dark brown,  $\text{SiO}_2$  surface; orange, 3 nm height above the  $\text{SiO}_2$  surface. (C) AFM image of single-layer graphene. Colors: dark brown,  $\text{SiO}_2$  surface; brown-red (central area), 0.8 nm height; yellow-brown (bottom left), 1.2 nm; orange (top left), 2.5 nm. Notice the folded part of the film near the bottom, which exhibits a differential height of  $\sim 0.4$  nm. For details of AFM imaging of single-layer graphene, see (15). (D) Scanning electron microscope image of one of our experimental devices prepared from FLG. (E) Schematic view of the device in (D).



**Fig. 2.** Field effect in FLG. (A) Typical dependences of FLG's resistivity  $\rho$  on gate voltage for different temperatures ( $T = 5, 70,$  and  $300$  K for top to bottom curves, respectively). (B) Example of changes in the film's conductivity  $\sigma = 1/\rho(V_g)$  obtained by inverting the 70 K curve (dots). (C) Hall coefficient  $R_H$  versus  $V_g$  for the same film;  $T = 5$  K. (D) Temperature dependence of carrier concentration  $n_0$  in the mixed state for the film in (A) (open circles), a thicker FLG film (squares), and multilayer graphene ( $d \approx 5$  nm; solid circles). Red curves in (B) to (D) are the dependences calculated from our model of a 2D semimetal illustrated by insets in (C).



***largest known  
flat hydrocarbon:  
222 atoms or 37 benzene rings  
(K. Müllen 2002)***



# GRAPHENE

0.142 nm

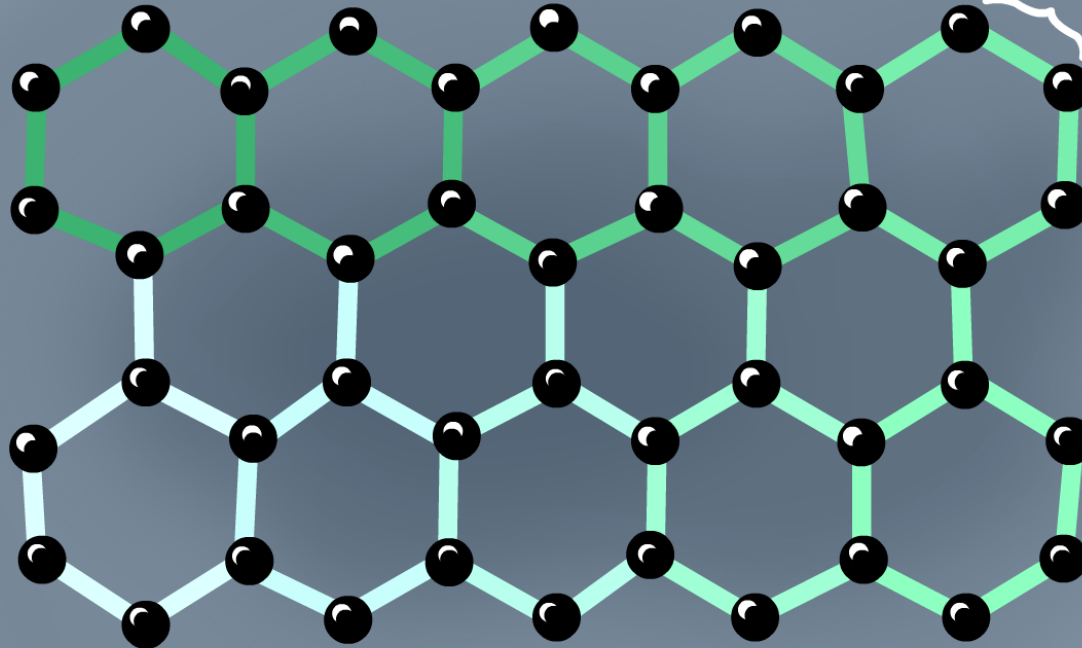
LIGHT!

RIGID

100x  
STRONGER  
THAN  
STEEL

PERFECT  
THERMAL  
CONDUCTOR

A CRYSTALLINE ALLOTROPE OF CARBON



# Properties

Graphene has no band gap

The top five industries that target the production of graphene is in Life Sciences for medical device, electronics TV, chemical biosensors, smart phone and smart pad and desalinization membranes.

**Strength and stiffness:** some 200 times stronger than steel, elastic like rubber

**Thinness and lightness**

**Heat conductivity:** it has very high thermal conductivity than any other material—better by far than brilliant heat conductors such as silver and copper

**Electrical conductivity** carrying electricity better than even superb conductors such as copper and almost as well as superconductors

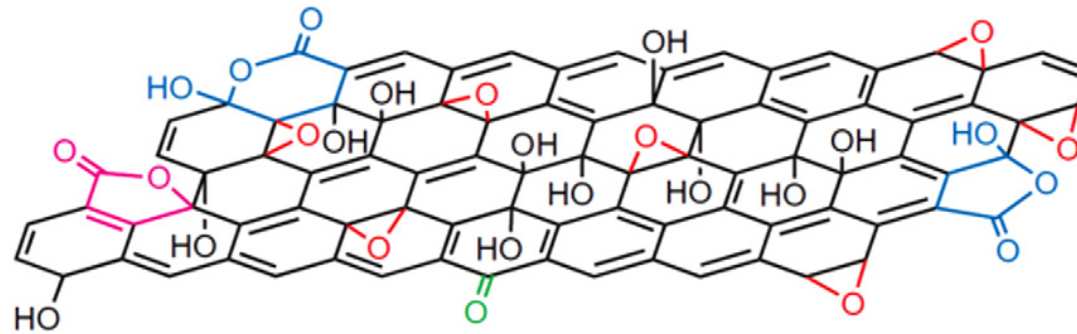
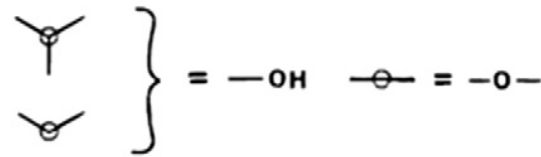
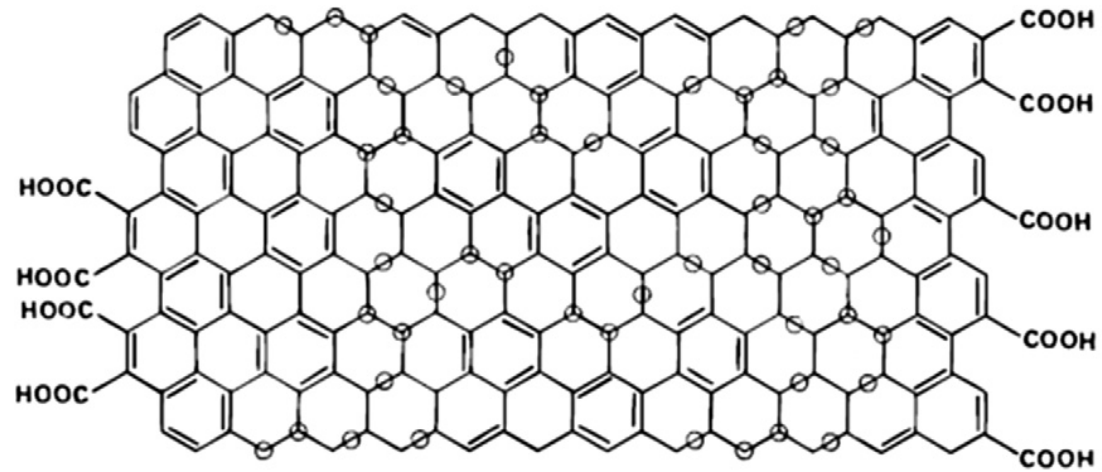
**Electronic properties**

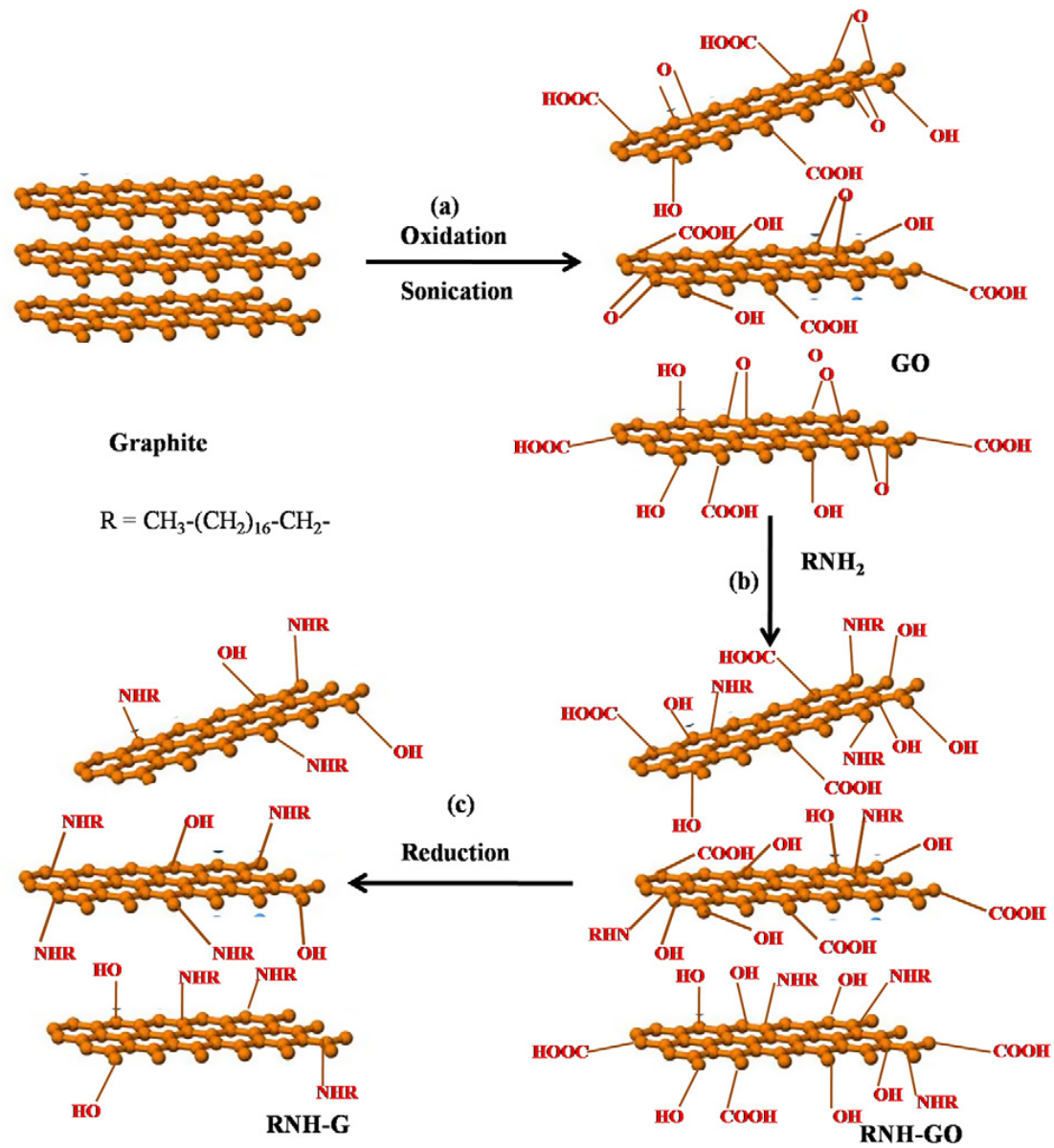
**Optical properties:** it is transparent

**Impermeability**

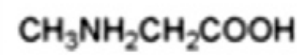
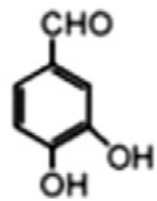
# Functionalization

oxidation

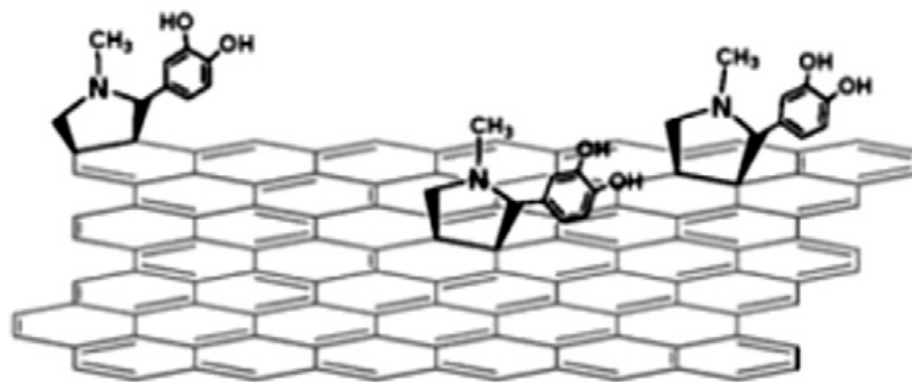




Graphene



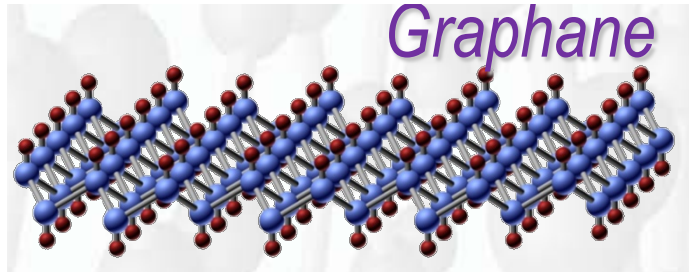
DMF, reflux 96 h



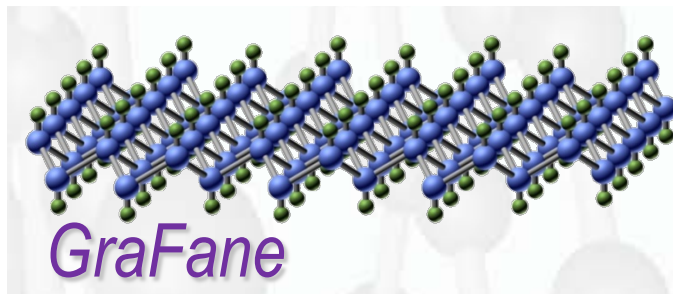
Graphene-*f*-OH



hydrogenation of graphene



Science 2009



fluorographene

Small 2010

# Graphene: applications

The exceptional electron and thermal transport, mechanical properties, barrier properties and high specific surface area of graphene and combinations thereof make it a potentially disruptive technology across a raft of industries. In 2010, there were over 400 patents issued on graphene and 3,000 research papers published.

The European Union is funding a 10 year 1,000 million euro coordination action on graphene.

## **Graphene Flagship**

South Korea is set to spend \$350 million on commercialization initiatives and the United Kingdom has announced investment of £50million in a new commercialization hub.