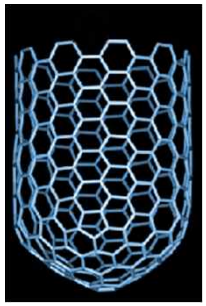
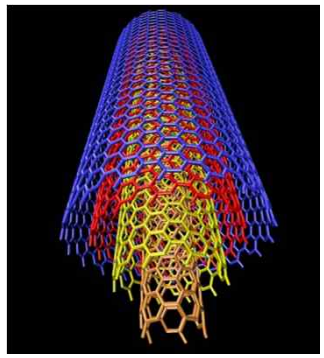
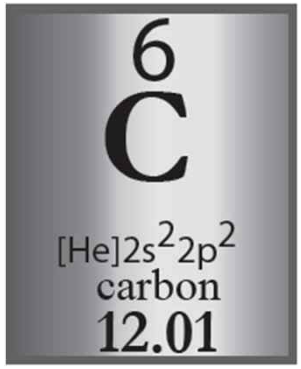
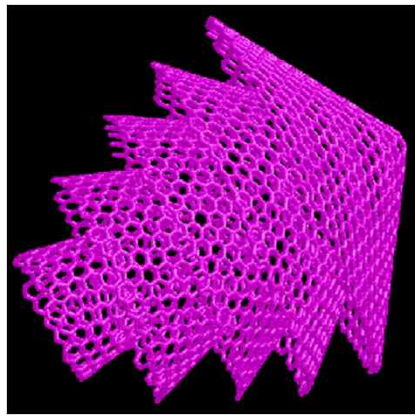
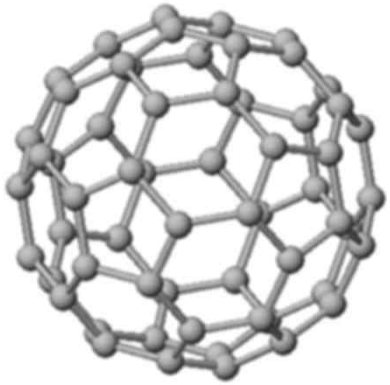








Nanocarbon: Properties and Applications

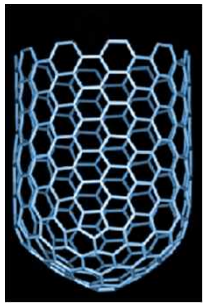


Trial lecture

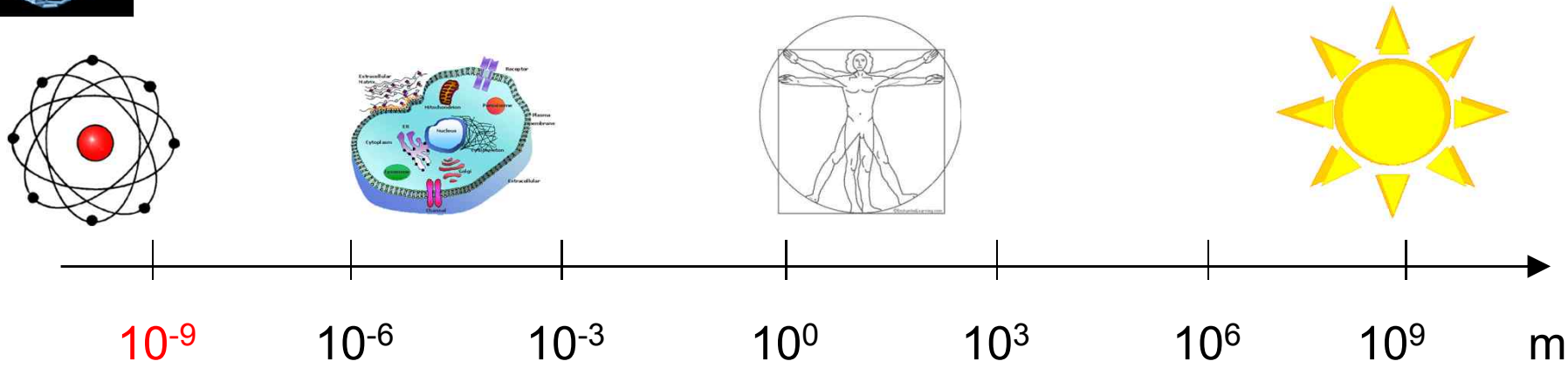
17/1-2004

Kai de Lange Kristiansen

(being available in an internet space)

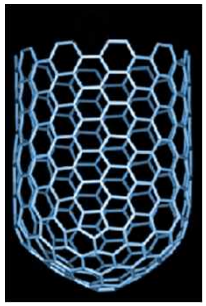


Nano



- Size – 10^{-9} m (1 nanometer)
- Border to quantum mechanics
- Form

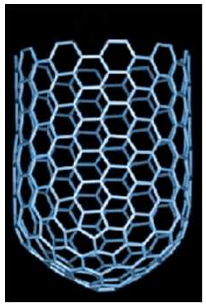
  → Emergent behavior



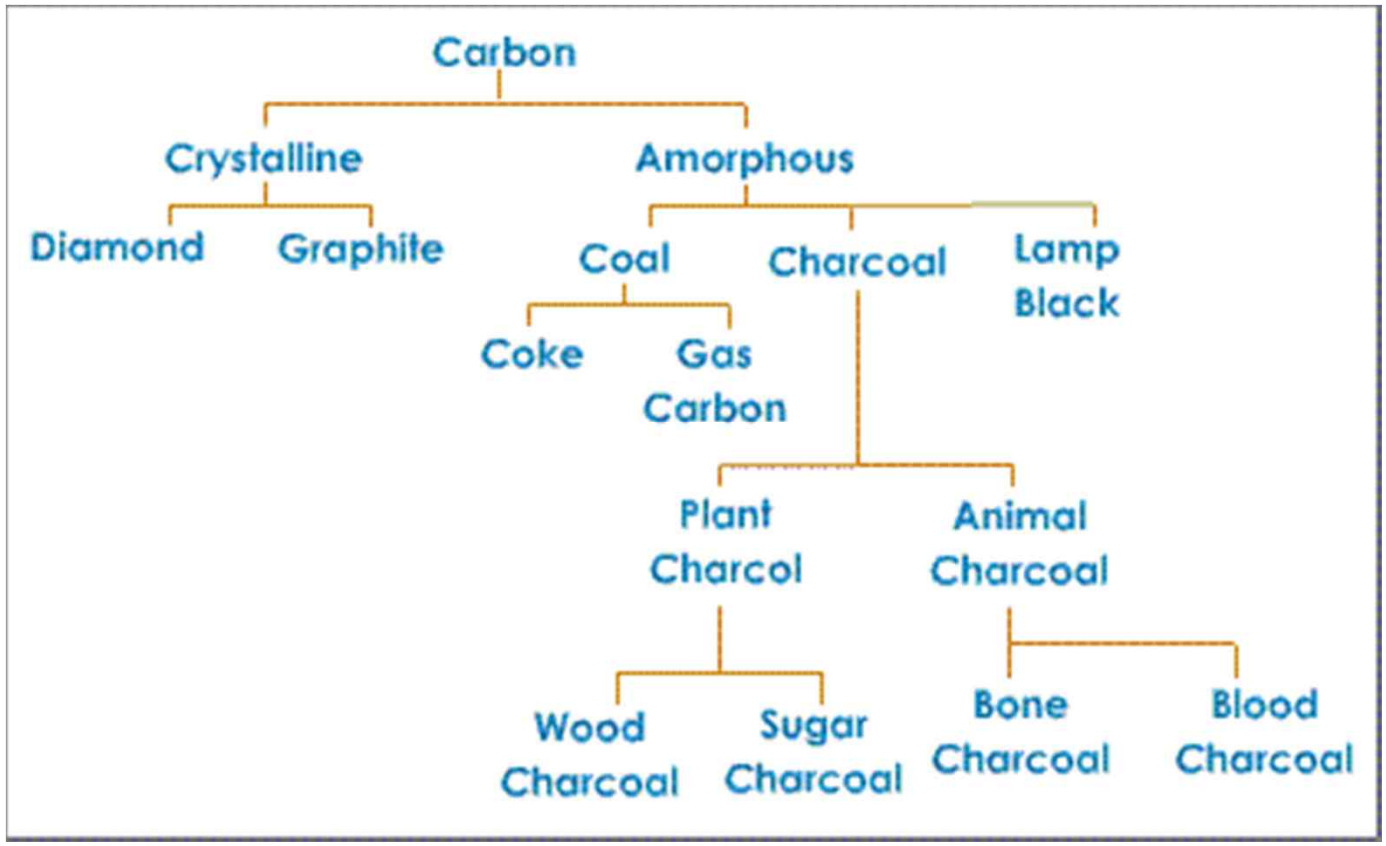
Carbon

6
C
[He]$2s^2 2p^2$
carbon
12.01

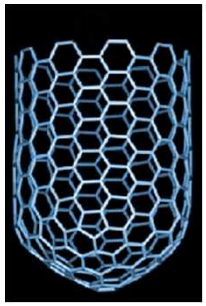
- Melting point: ~ 3500°C
- Atomic radius: 0.077 nm
- Basis in all organic componds
- 10 mill. carbon componds



Allotropy and Allotropes of Carbon (Family)

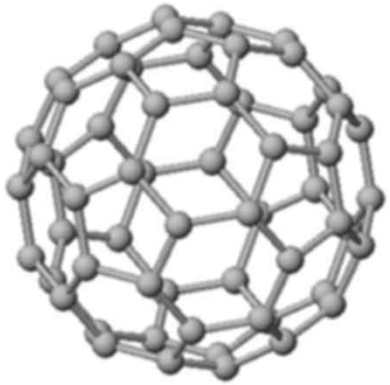


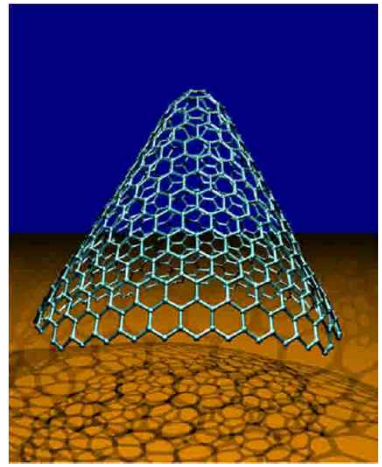
http://chemistry.tutorvista.com/inorganic-chemistry/allotropes-of-carbon.html

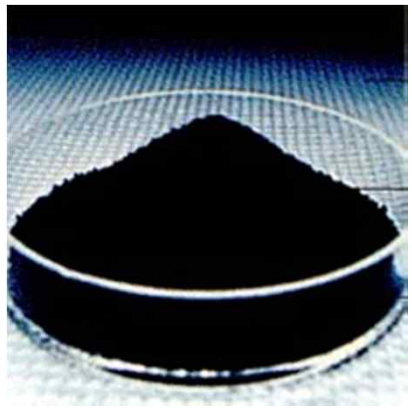


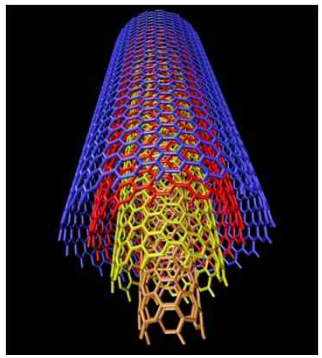
Nanocarbon

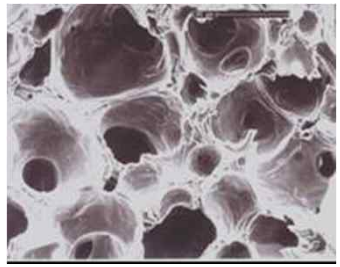
- Fullerene
- Tubes
- Cones
- Carbon black
- Horns
- Rods
- Foams
- Nanodiamonds

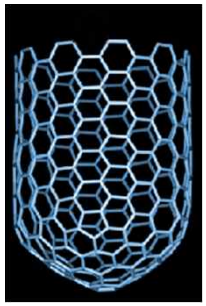






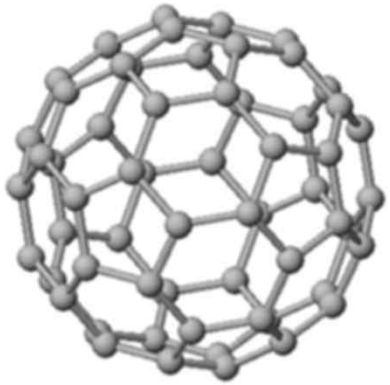


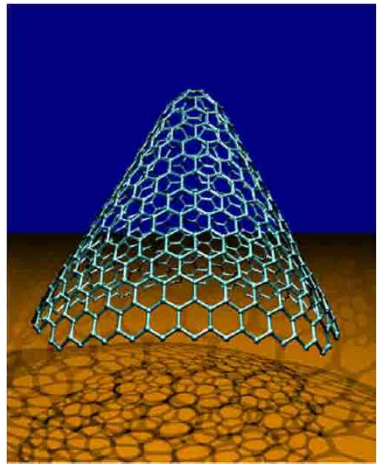


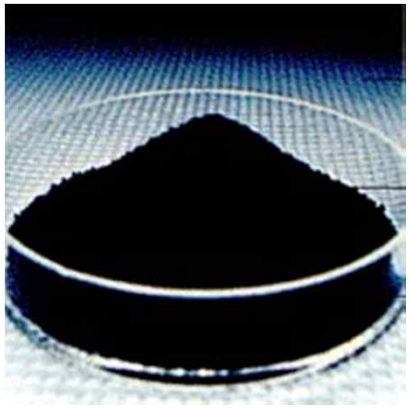


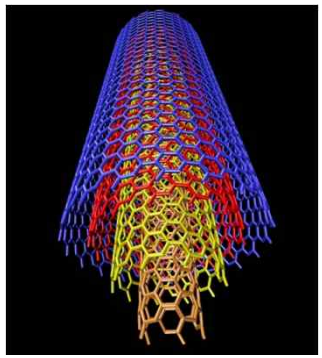
Nanocarbon

- Fullerene
- Tubes
- Cones
- Carbon black



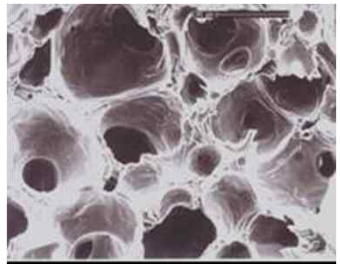


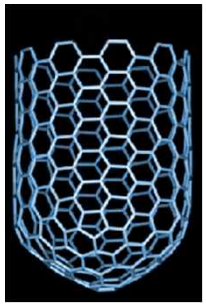




Properties & Application

- Electrical
- Mechanical
- Thermal
- Storage

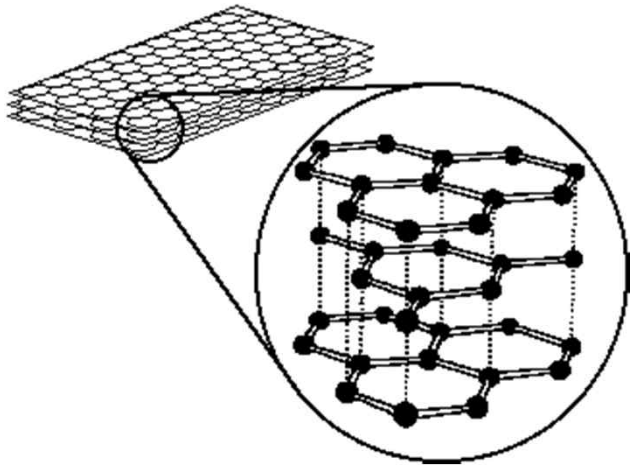


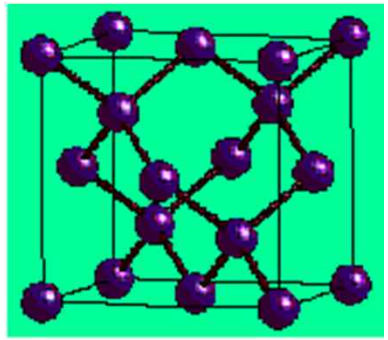


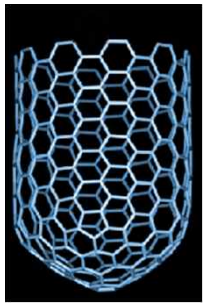
Bonding

Graphite – sp^2

Diamond – sp^3

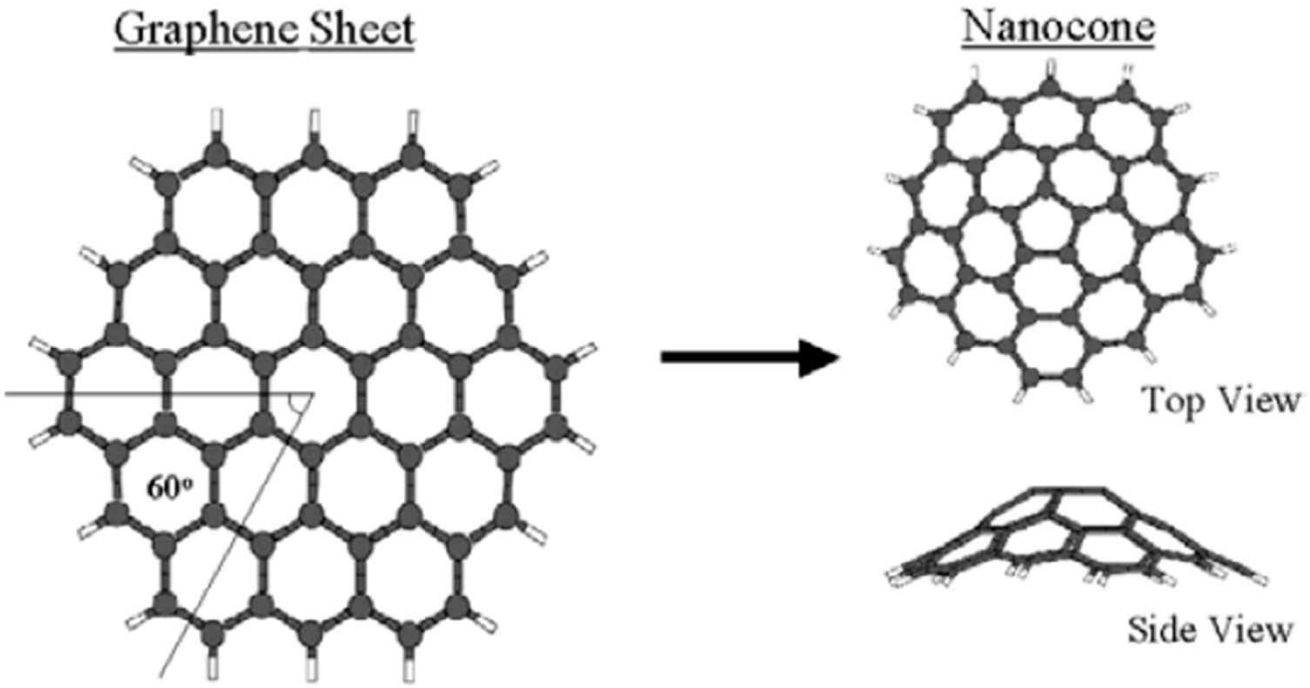




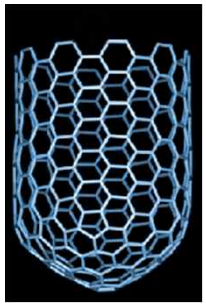


Properties

Nanocarbon



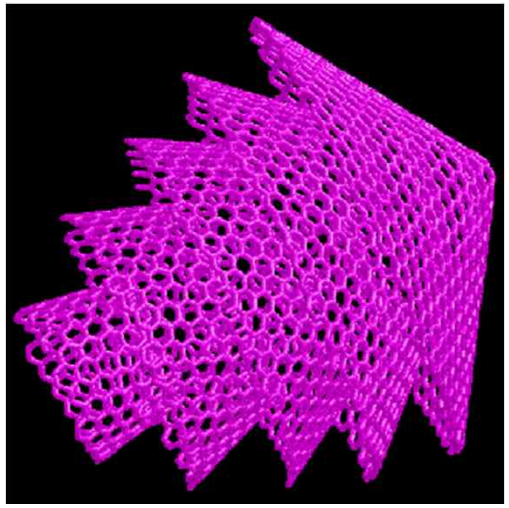
Shenderova *et al*.
Nanotechnology **12** (2001) 191.



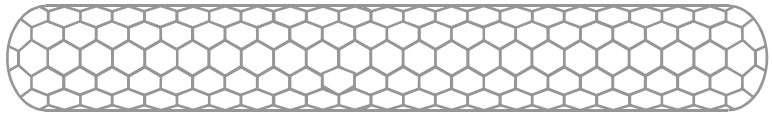
Properties

Nanocarbon

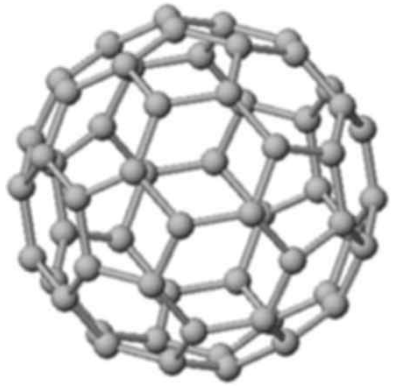
1 – 5 pentagons

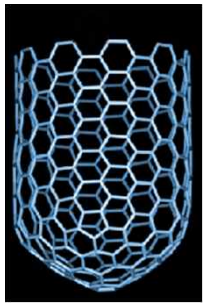


6 + 6 pentagons



12 pentagons





Properties

Fullerene

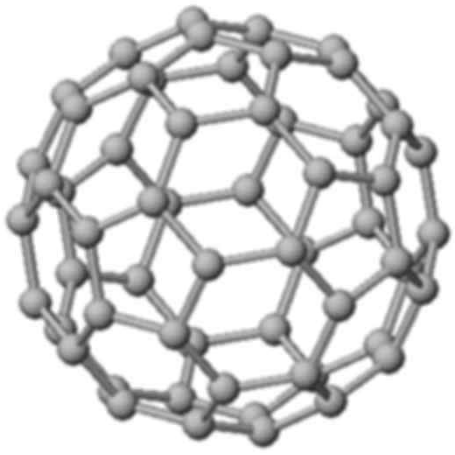
”The most symmetrical large molecule”

- Discovered in 1985

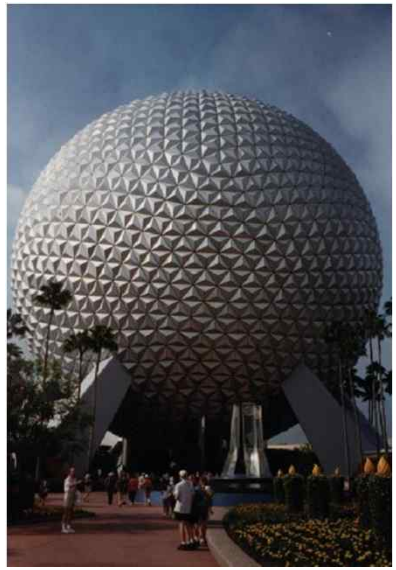
  - Nobel prize Chemistry 1996, Curl, Kroto, and Smalley

- C_{60}, also 70, 76 and 84.
  - 32 facets (12 pentagons and 20 hexagons)
  - prototype

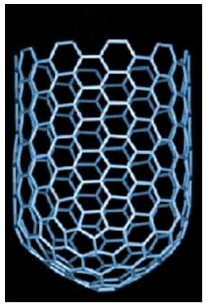
~1 nm



Epcot center, Paris

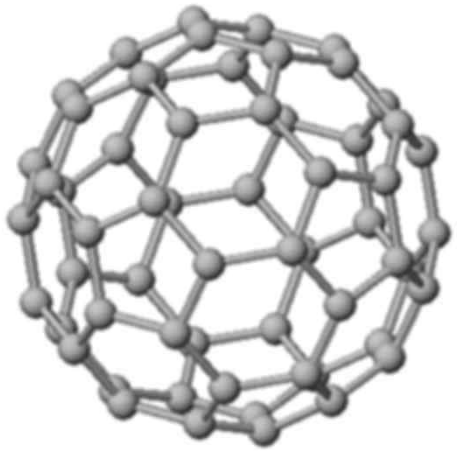


Architect: R. Buckminster Fuller

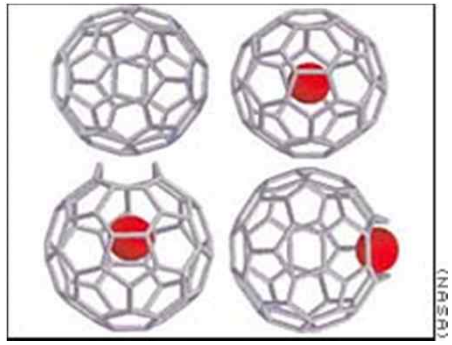


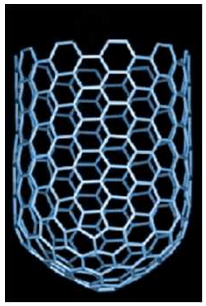
Properties

Fullerene



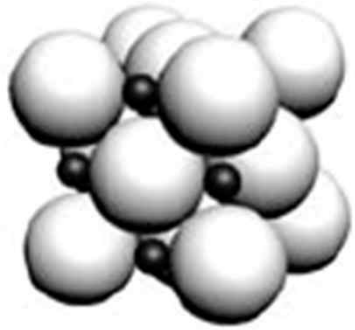
- Symmetric shape
  → lubricant
- Large surface area
  → catalyst
- High temperature (~500°C)
- High pressure
- Hollow
  → caging particles
- Ferromagnet?
  - polymerized C_{60}
  - up to 220°C

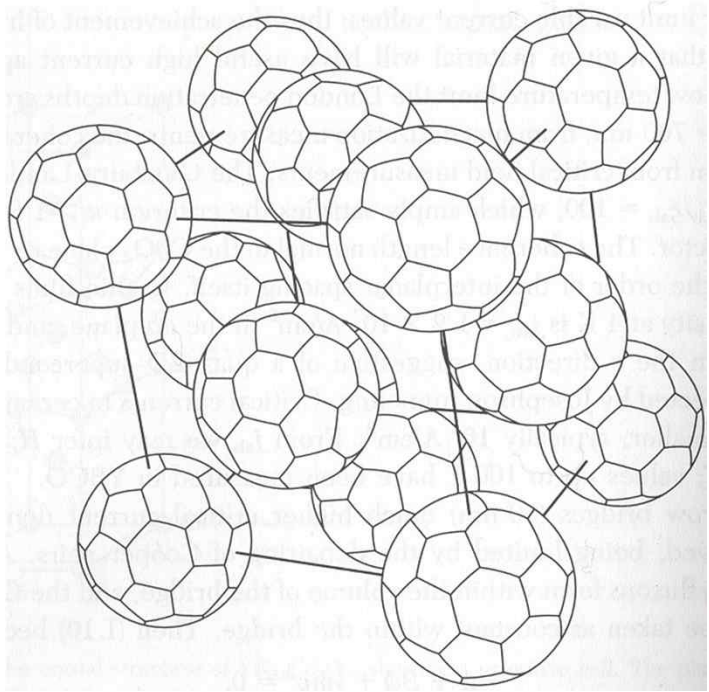




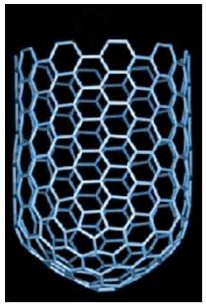
Fullerene

- Chemically stable as graphite
  - most reactive at pentagons
- Crystal by weak van der Waals force
- Superconductivity
  - K_3C_{60}: 19.2 K
  - $RbCs_2C_{60}$: 33 K



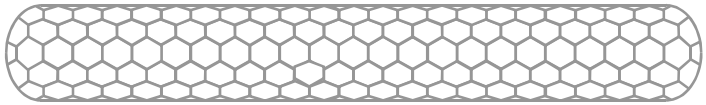


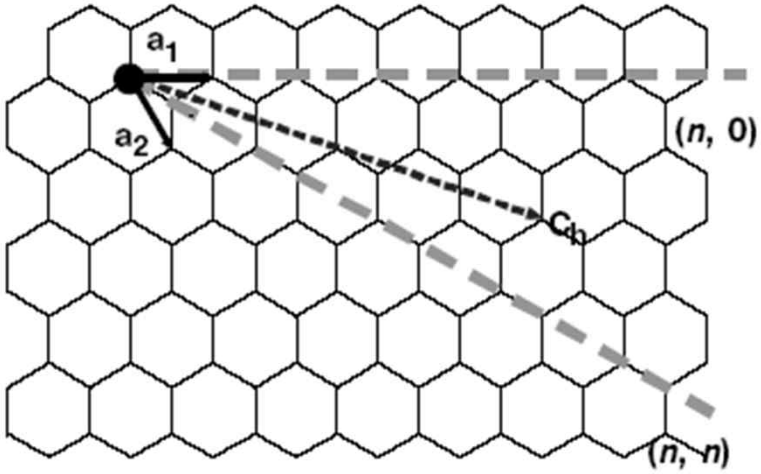
Kittel, *Introduction to Solid State Physics*, 7the ed. 1996.

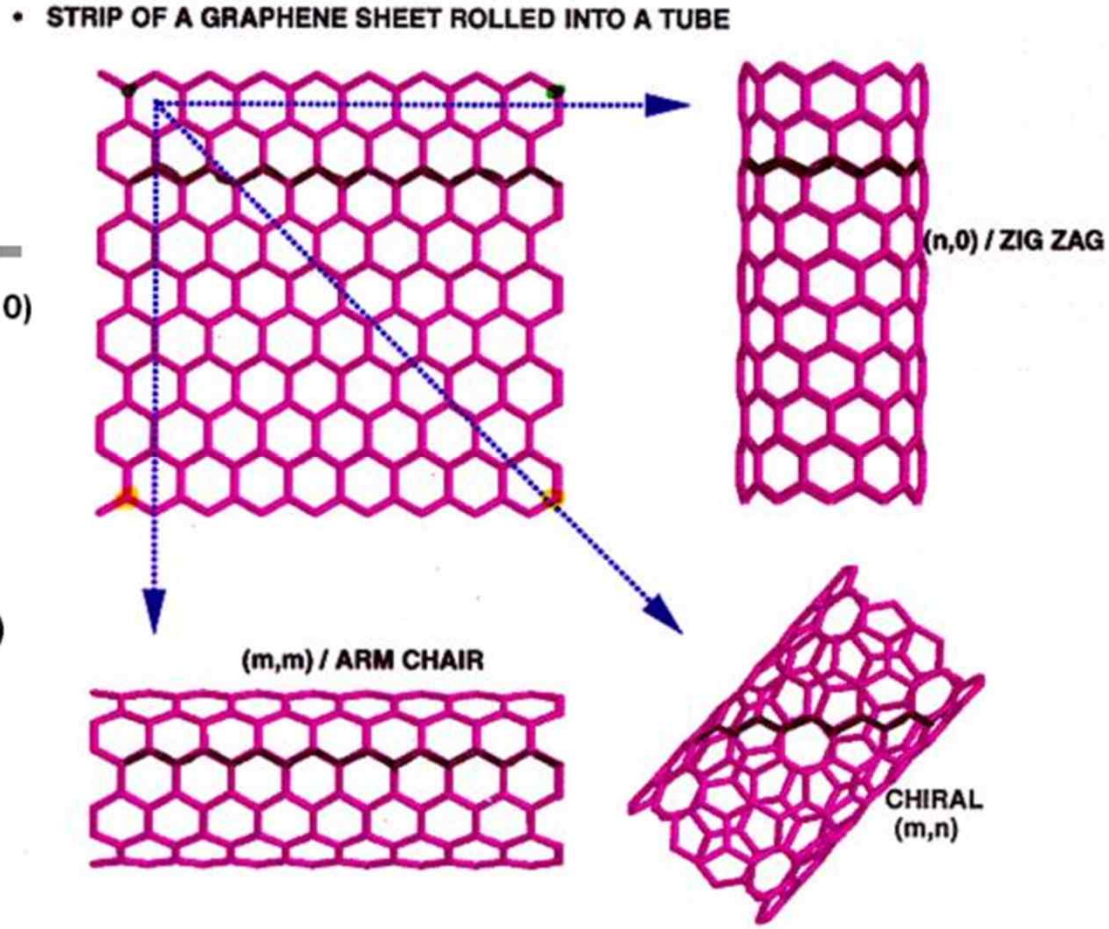


Nanotube

- Discovered 1991, Iijima

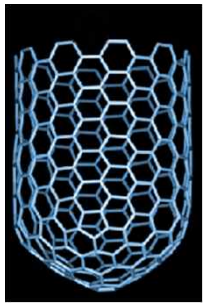






Roll-up vector:

$$C_h = n\vec{a}_1 + m\vec{a}_2$$



Properties

Nanotube

Electrical conductanse depending on helicity

$$C_h = n\vec{a}_1 + m\vec{a}_2$$ If $$\frac{2n+m}{3} = i$$, then metallic
else semiconductor

- Current capacity

  Carbon nanotube 1 GAmps / cm^2

  Copper wire 1 MAmps / cm^2

- Heat transmission

  Comparable to pure diamond (3320 W / m·K)

- Temperature stability

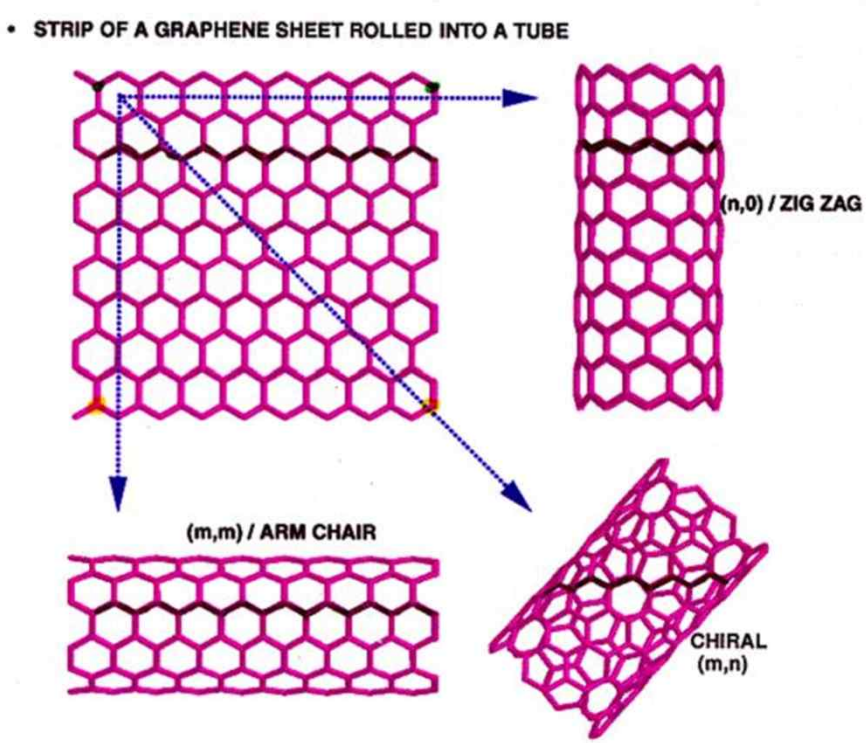
  Carbon nanotube 750 °C (in air)

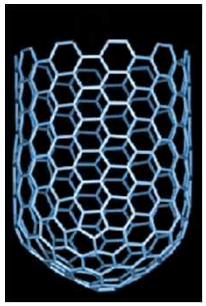
  Metal wires in microchips 600 – 1000 °C

- Caging

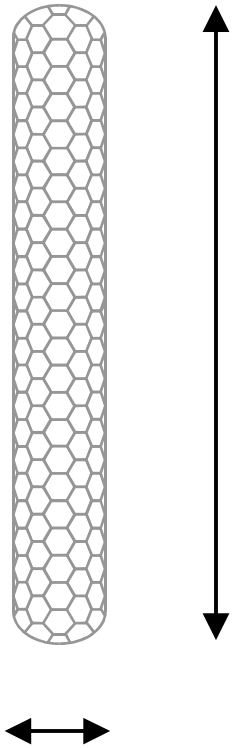
  May change electrical properties

  → sensor





Nanotube



Length:

typical few µm

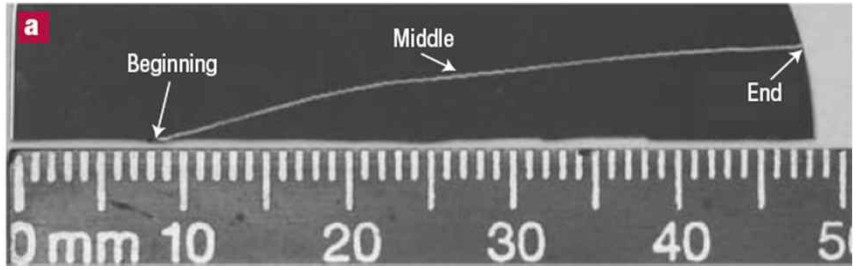
High aspect ratio:

$$\frac{length}{diameter} > 1000$$

→ quasi 1D solid

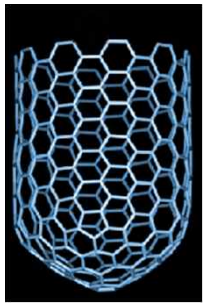
Diameter:

as low as 1 nm



SWCNT – 1.9 nm

Zheng *et al*. Nature Materials **3** (2004) 673.



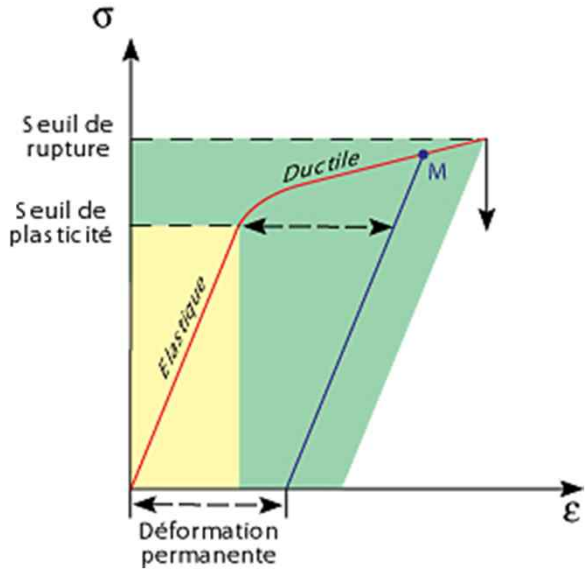
Properties

Nanotubes

Carbon nanotubes are the strongest ever known material.

- **Young Modulus (stiffness):**

Carbon nanotubes	1250 GPa
Carbon fibers	425 GPa (max.)
High strength steel	200 GPa

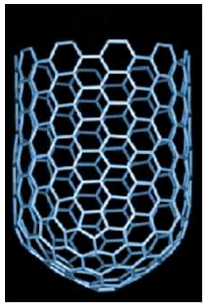


- **Tensile strength (breaking strength)**

Carbon nanotubes	11- 63 GPa
Carbon fibers	3.5 - 6 GPa
High strength steel	~ 2 GPa

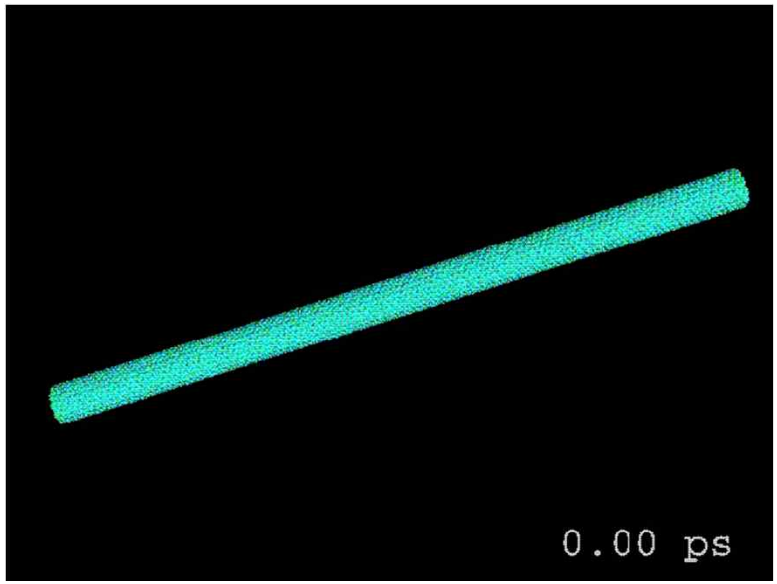
- **Elongation to failure : ~ 20-30 %**
- **Density:**

Carbon nanotube (SW)	1.33 – 1.40 gram / cm^3
Aluminium	2.7 gram / cm^3

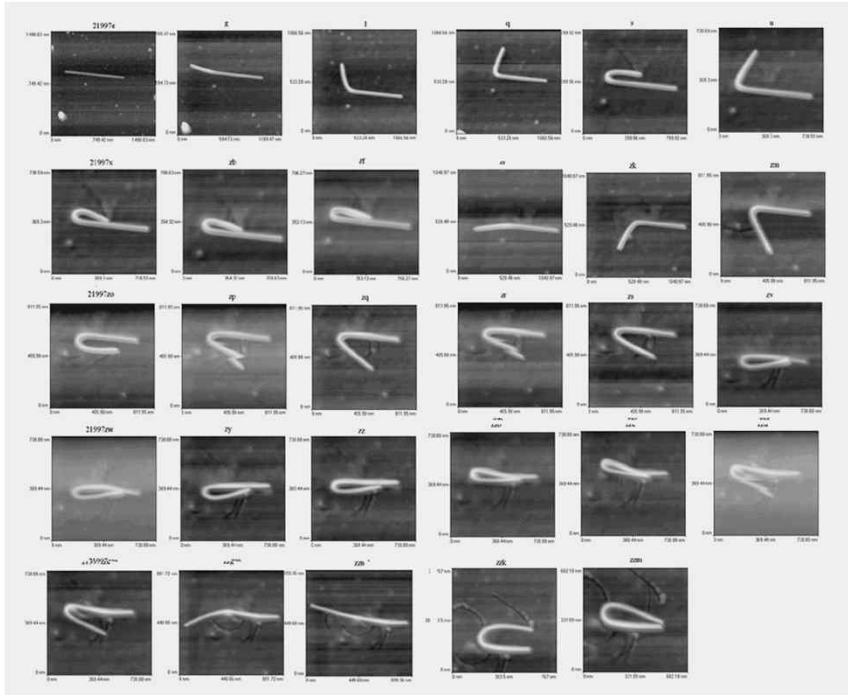


Mechanical

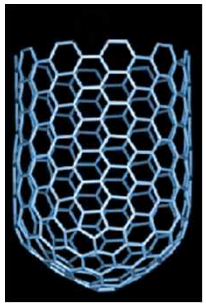
- Carbon nanotubes are very flexible



http://www.ipt.arc.nasa.gov/gallery.html



Nanoscience Research Group
University of North Carolina (USA)
http://www.physics.unc.edu/~rsuper/research/



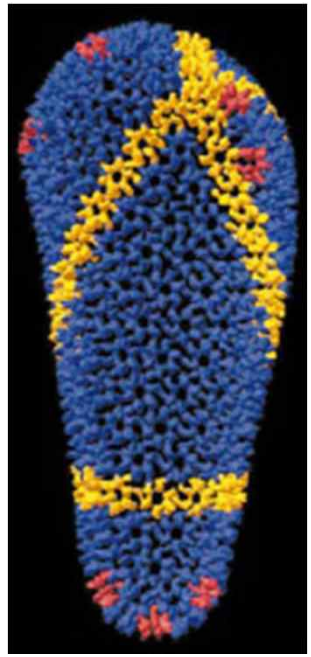
Cones

- Discovered 1994 (closed form) Ge & Sattler

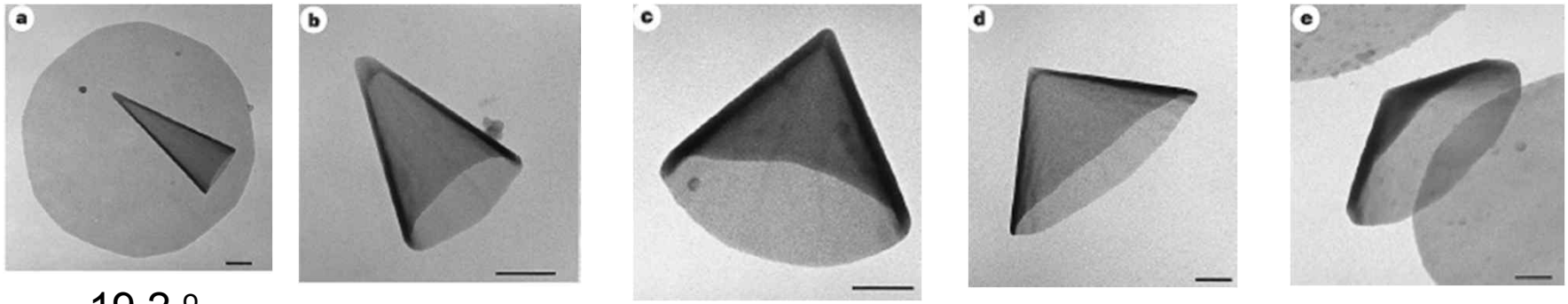
  1997 (open form) Ebbesen *et al*.

- Closed: same shape as HIV capsid
- Possible scale-up production (open form)
- Storage?

  → Hydrogen



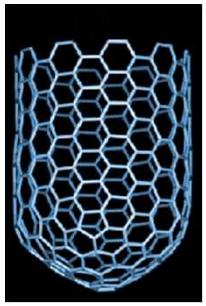
Li *et al*. Nature **407** (2000) 409.



19.2 º 38.9 º 60.0 º 84.6 º 112.9 º

Scale bar: 200 nm

Krishnan, Ebbesen *et al*. Nature **388** (2001) 241.



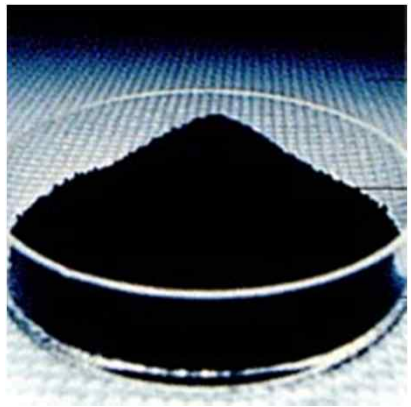
Carbon black

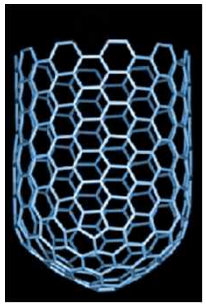
Large industry

- mill. tons each year

• Tires, black pigments, plastics, dry-cell batteries, UV-protection etc.

• Size: 10 – 400 nm



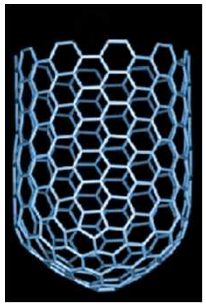


Application

Writing

Carbon – graphite

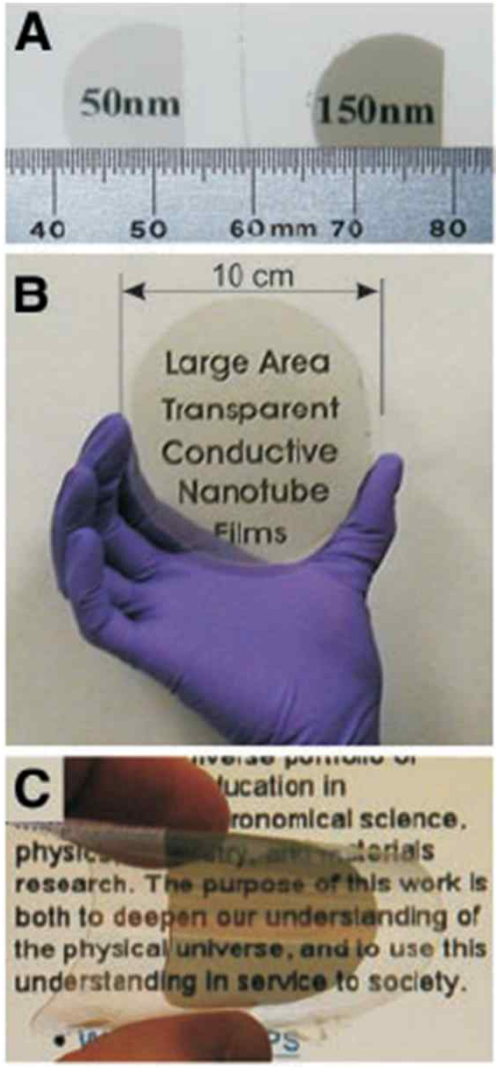
C_{60}: 1000x better resolution than ink (Xerox)



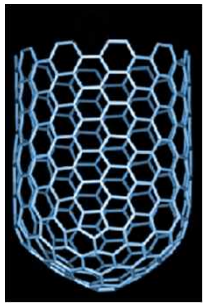
Application

CNT / polymer composite

- Transparent electrical conductor
  - Thickness: 50 – 150 nm
  - High flexibility



Wu *et al*. Science **305** (2004) 1273.

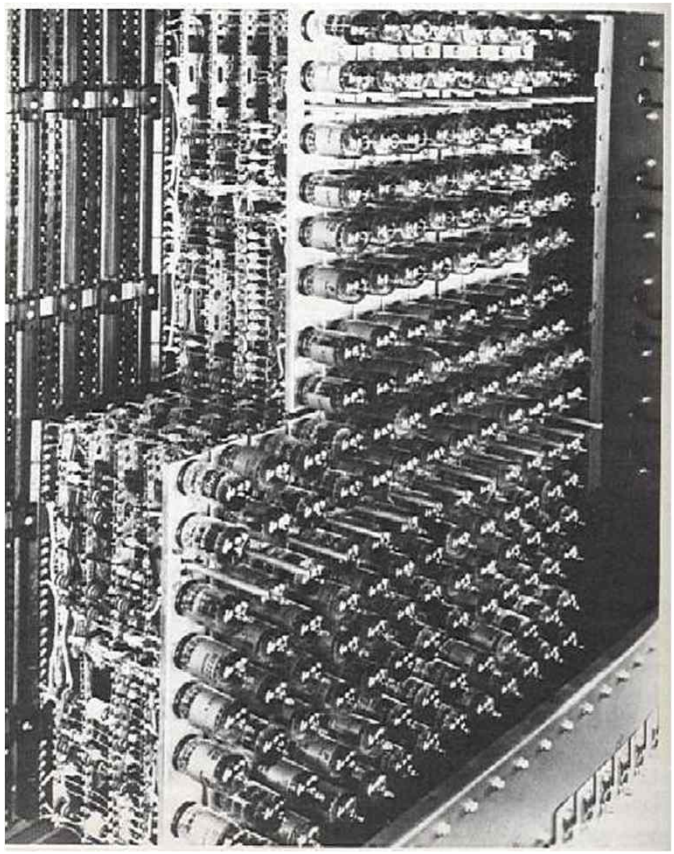


Application

Transistor

- Vacuum tubes

  - Nobel prize 1906, Thomson.

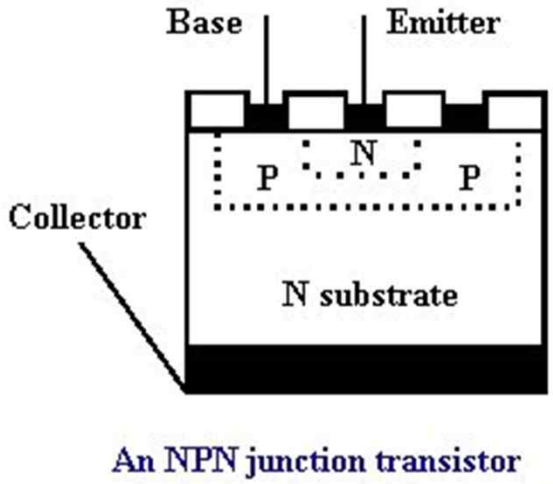


IBM, 1952.

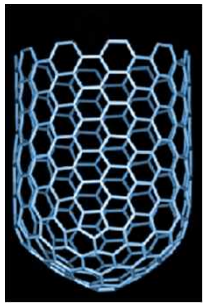
- Semiconductor, Si-based

  - Nobel prize 1956, Shockley, Bardeen, and Brattain.

  - 2000, Kilby.



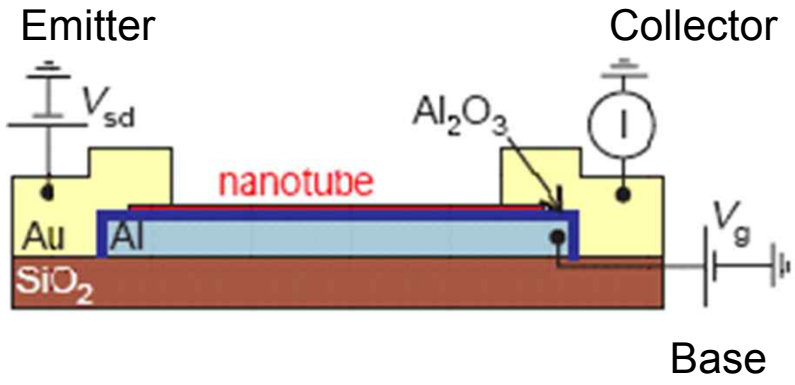
An NPN junction transistor

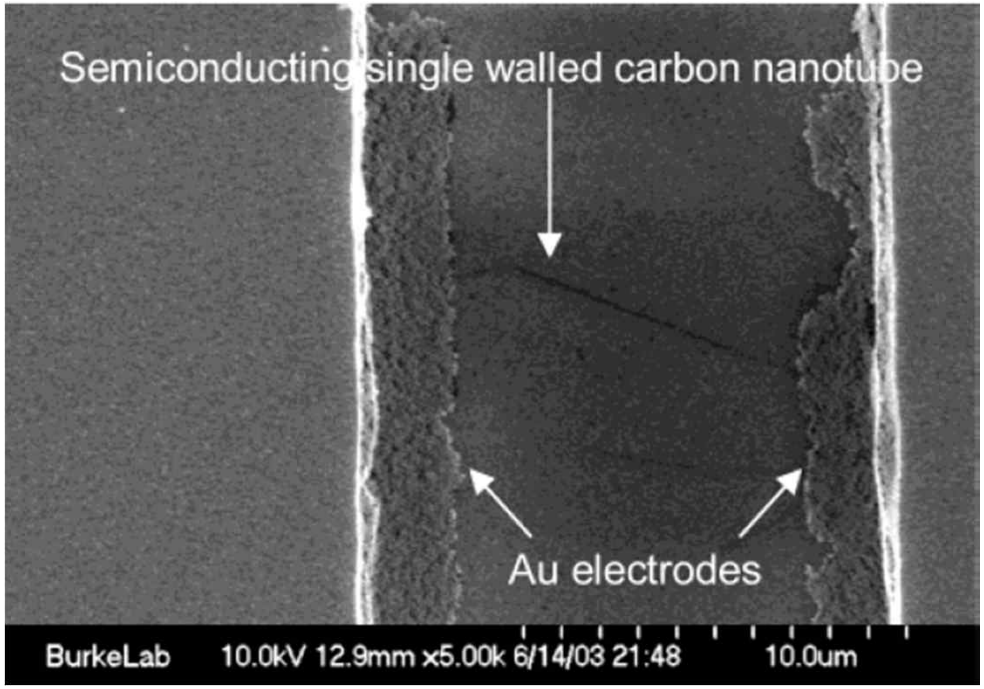


Application

Transistor

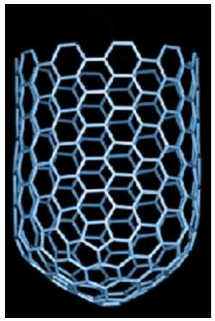
- SWCNT
  - 2.6 GHz, T = 4 K
  - Logical gates





Bachtold, Dekker *et al*.
Science **294** (2001) 1317.

Li *et al*. Nano Lett. **4** (2004) 753.



Application

Antenna

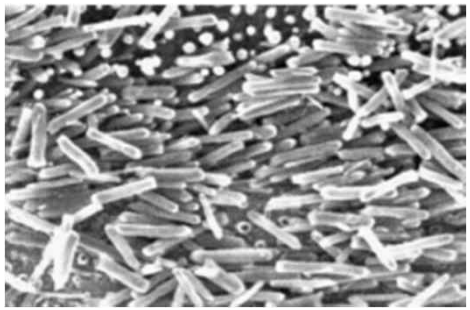
- Dipole

~ 3/4 m

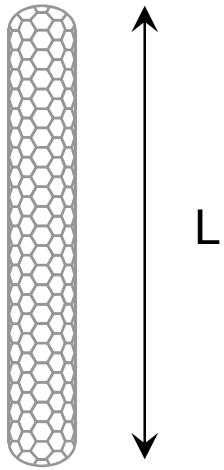
Radio wave:

$$f = \frac{c}{\lambda} = \frac{3 \cdot 10^8 \frac{m}{s}}{3\,m} \sim 100\,MHz$$

- Nanotube

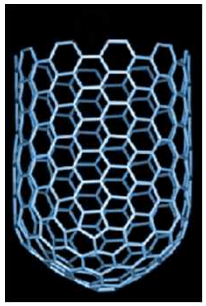


Dekker, Phys. Today May (1999) 22



Optical wave:

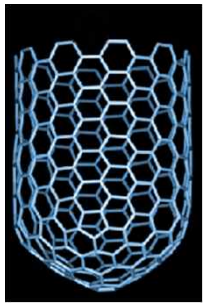
$$\lambda \sim L/2 \sim 500\,nm$$



Application

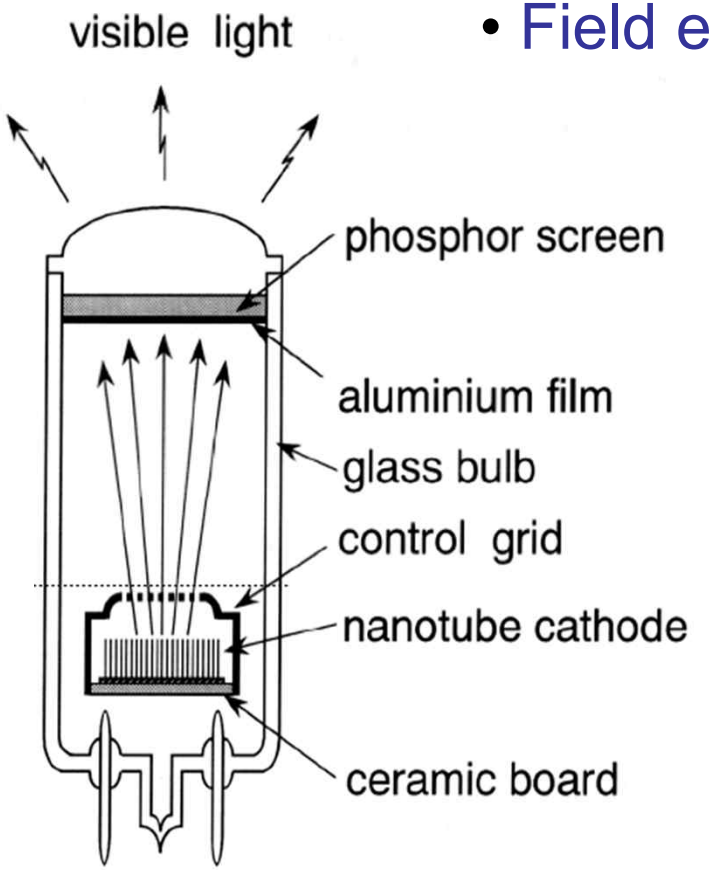
Flat screen displays

Plasma TV



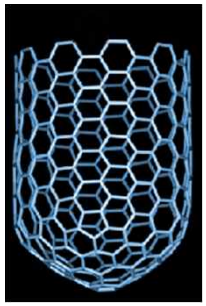
Application

Flat screen displays



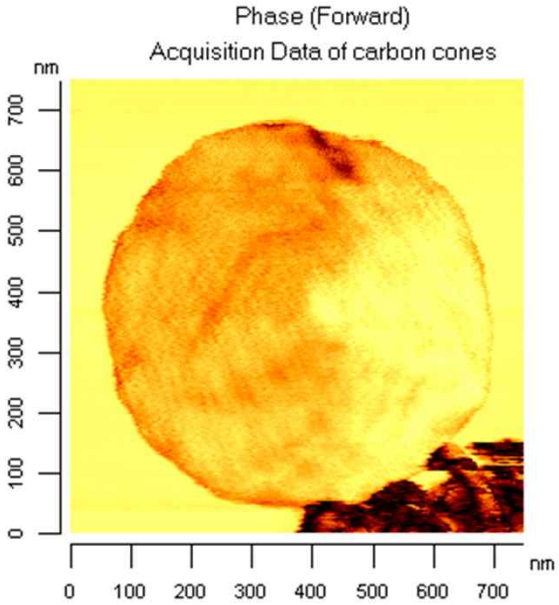
- Field emission

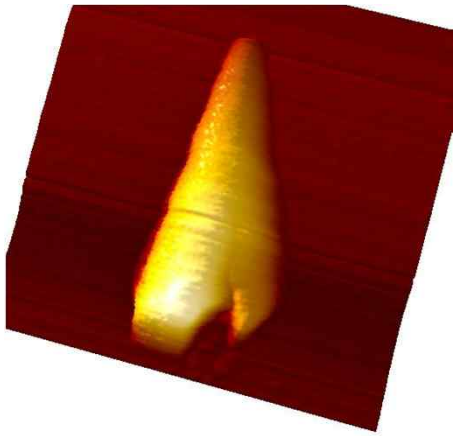
Saito *et al*., Jpn. J. Appl. Phys. **37** (1998) L346.

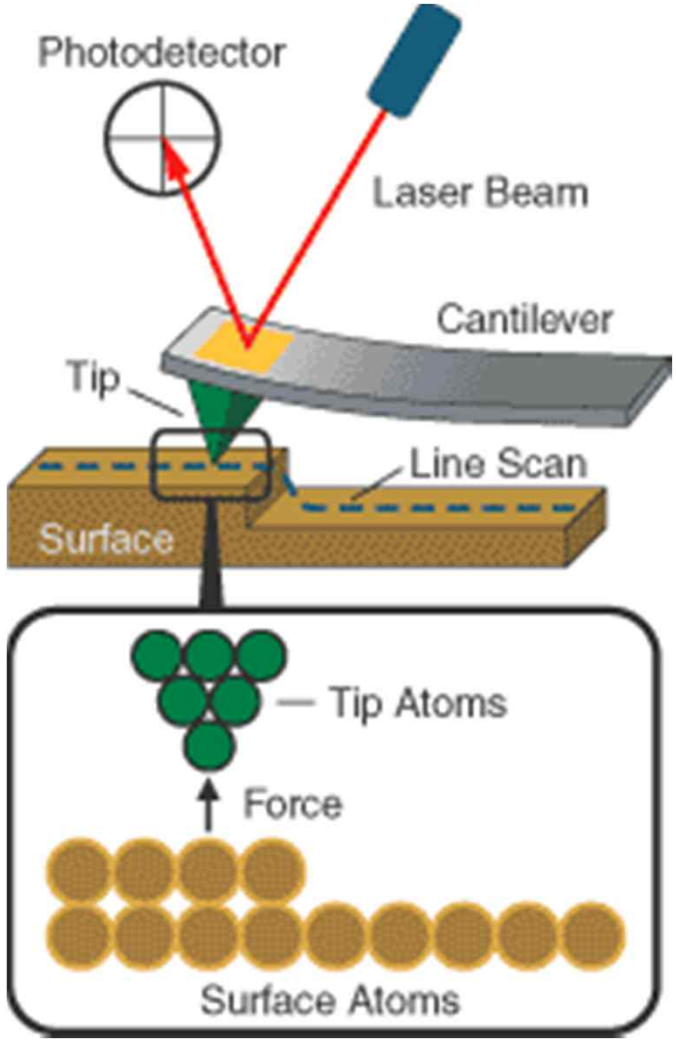


Application

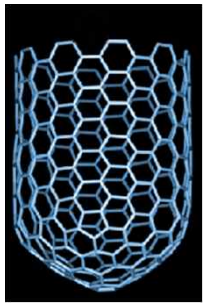
Atomic Force Microscopy







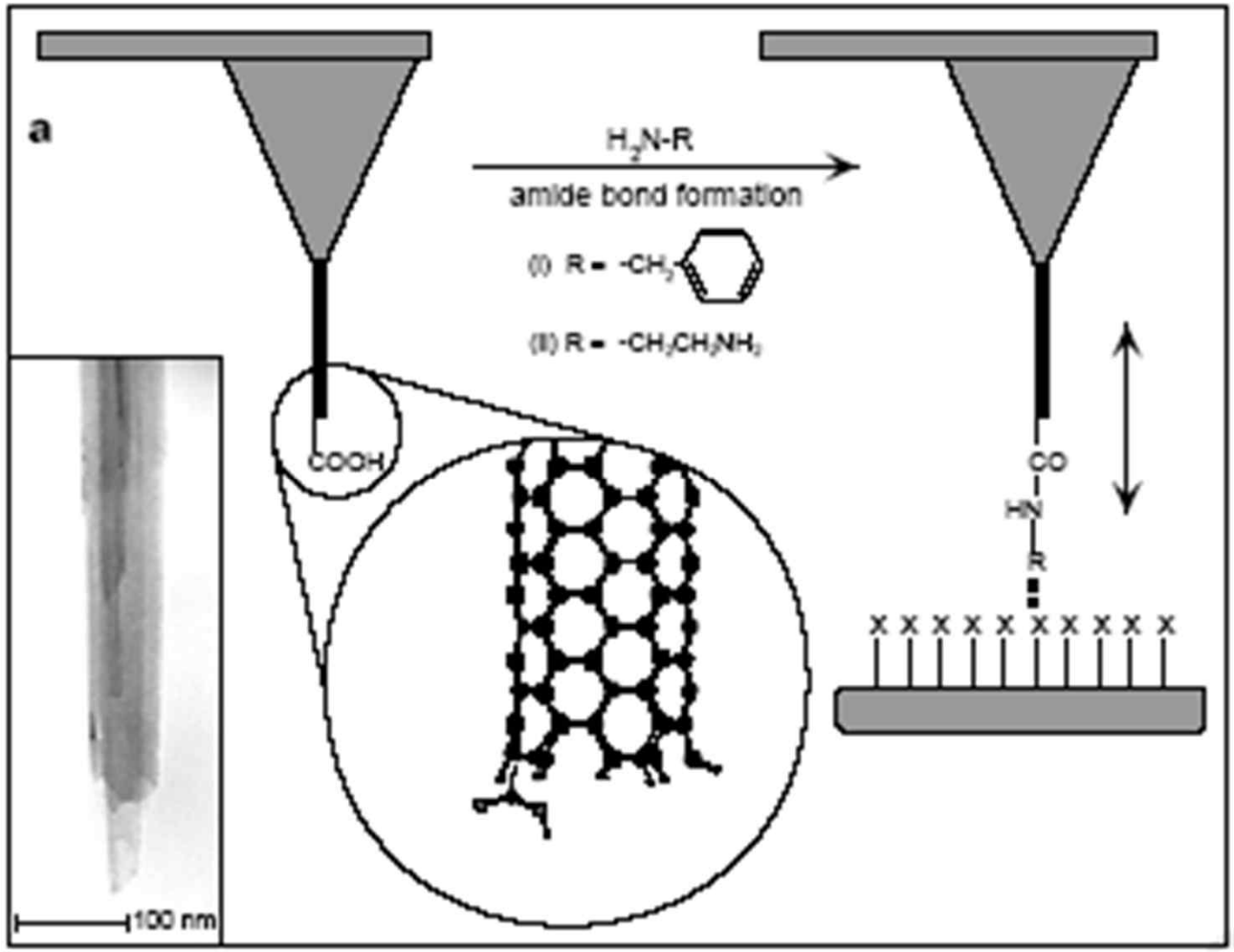
Eldrid Svåsand, IFE, Kjeller



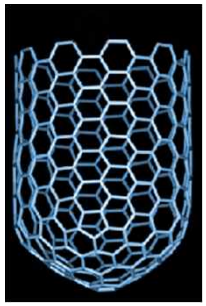
Application

Atomic force microscopy

- Tube or cone
- Chemical probe

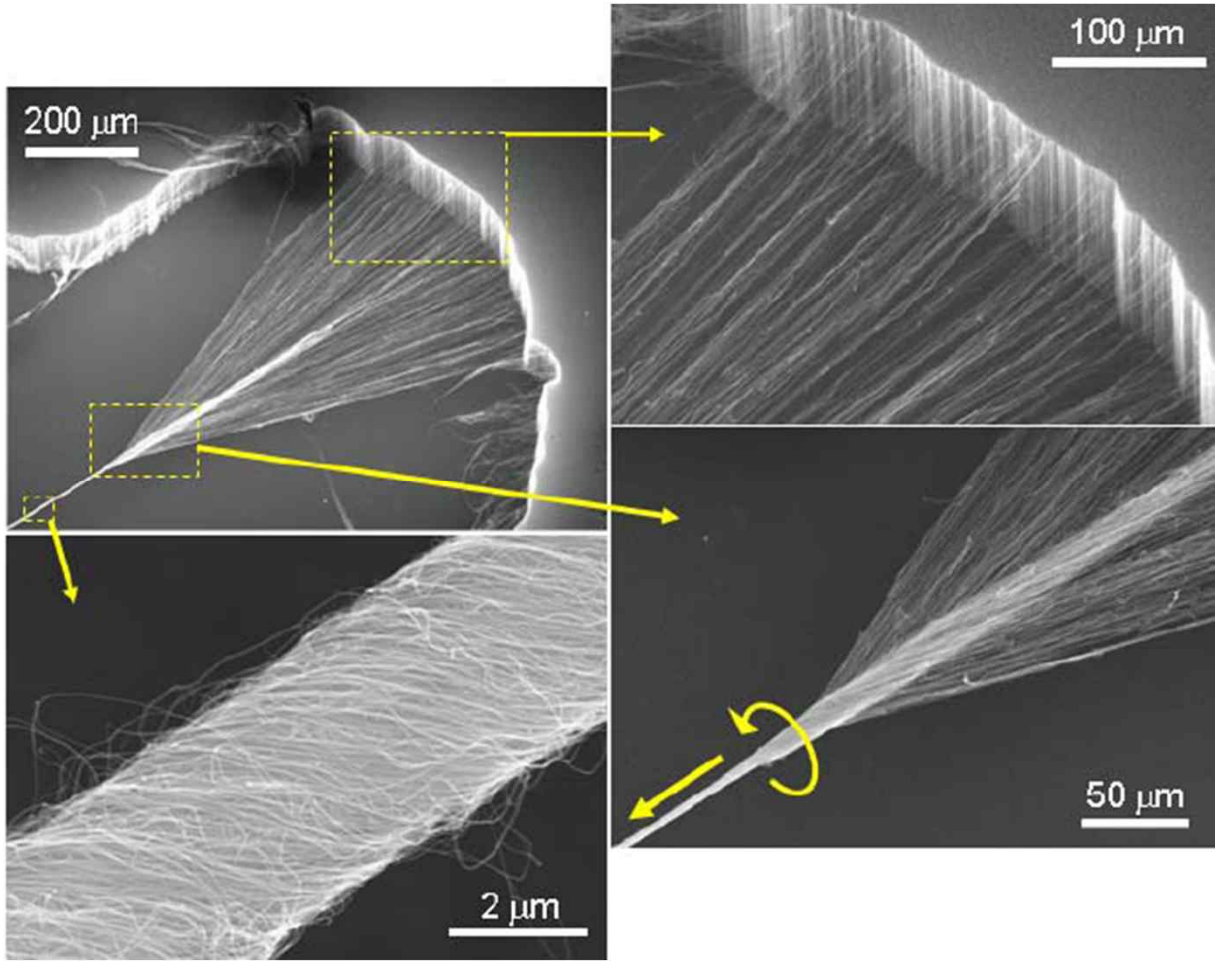


Wong, Lieber *et al*.
Nature **394** (1998) 52.

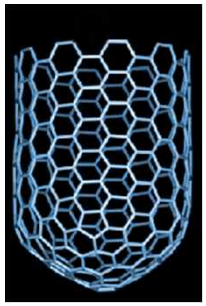


Application

Yarn



Zhang, Atkinson and Baughman,
Science **306** (2004) 1358.

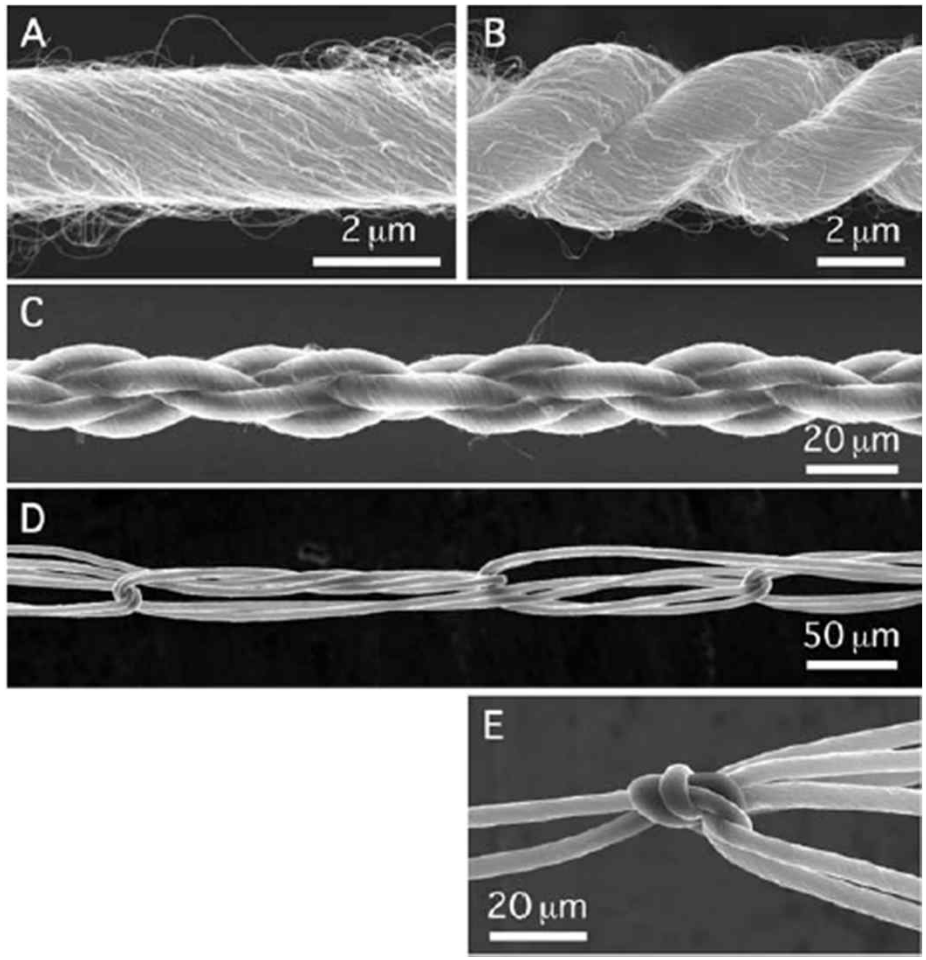


Application

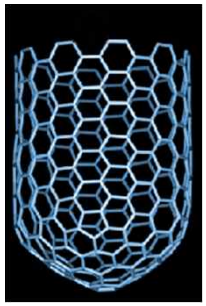
Yarn

MWCNT

- Operational -196°C < T < 450°C
- Electrical conducting
- Toughness comparable to Kevlar
- No rapture in knot



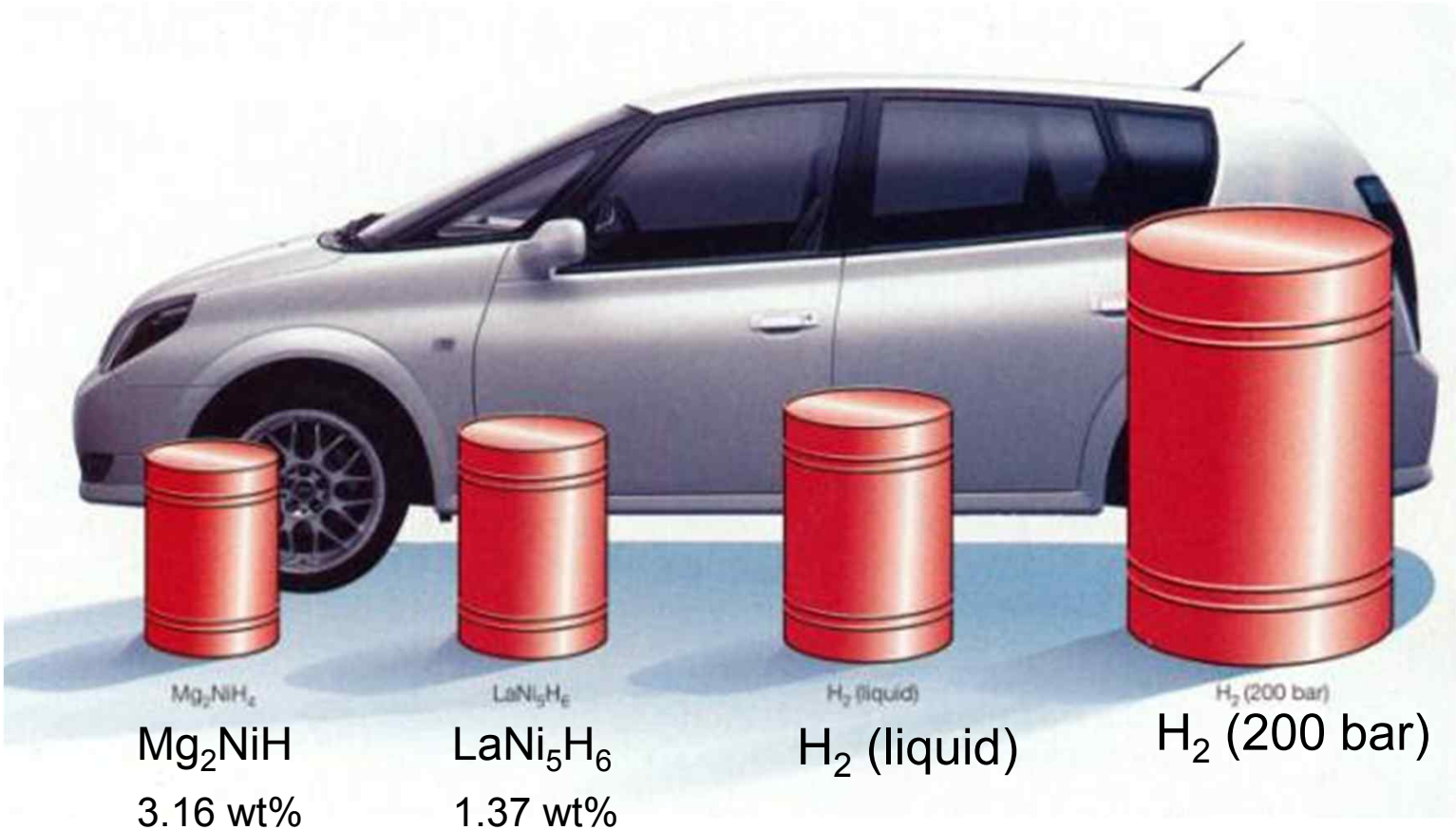
Zhang, Atkinson and Baughman, Science **306** (2004) 1358.



Application

Hydrogen storage

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O\ (l) + \text{energy}$$



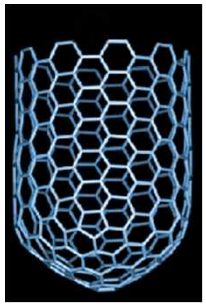
Mg_2NiH 3.16 wt%

$LaNi_5H_6$ 1.37 wt%

H_2 (liquid)

H_2 (200 bar)

Schlapbach & Züttel, Nature **414** (2001) 353



Application

Hydrogen storage

- Aim: 5 - 7 wt% H_2

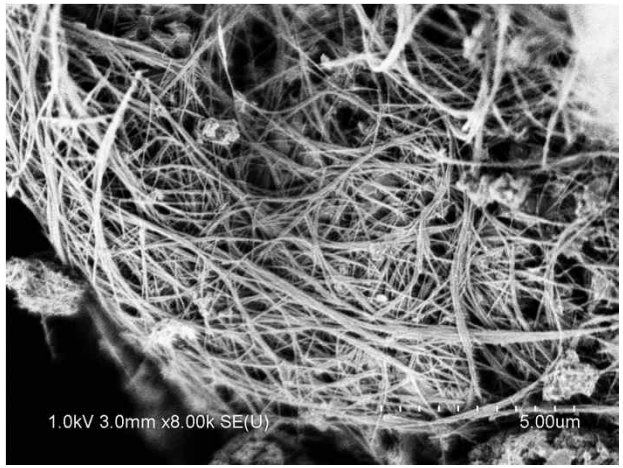
- SWCNT

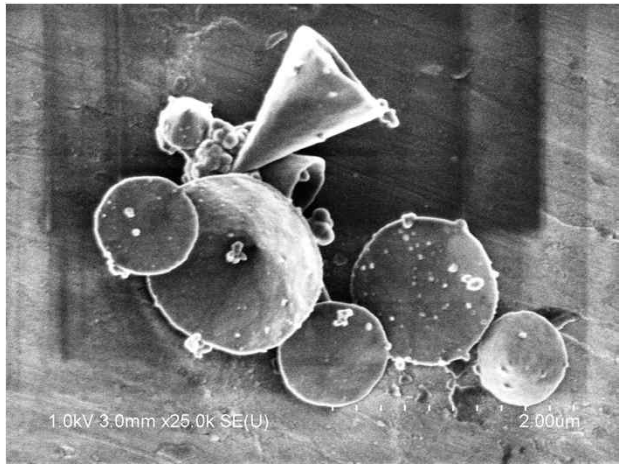
  - Dillon *et al.* (1997) : 8 wt% (questionable)

  - Tarasov *et al.* (2003): 2.4 wt% reversible, 25 bar H_2, - 150^{o}C.

- Cones

  - Mealand & Skjeltorp, (2001) US Patent 6,290,753





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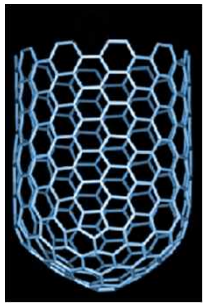
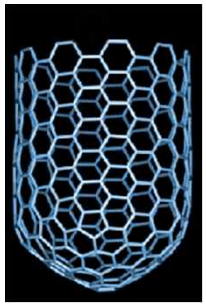


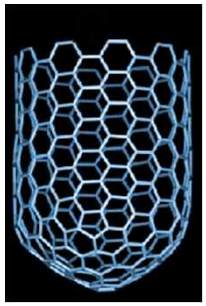
Warnings

- Environment and health
- No scale-up production of fullerenes and tubes
- No scale-up design, yet.



Summary

- Carbon comprises a number of allotropes
- Each has characteristic/novel properties
- Fabricating nanocarbon uses a number of approaches, each with special equipment
- Applications of nanocarbon include electronics, structural materials, and energy
- We are still at the beginning of a relatively long journey into nanocarbon engineering



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