MSc S4- Inorganic Chemistry
Nanomaterilas

PRESENTED BY

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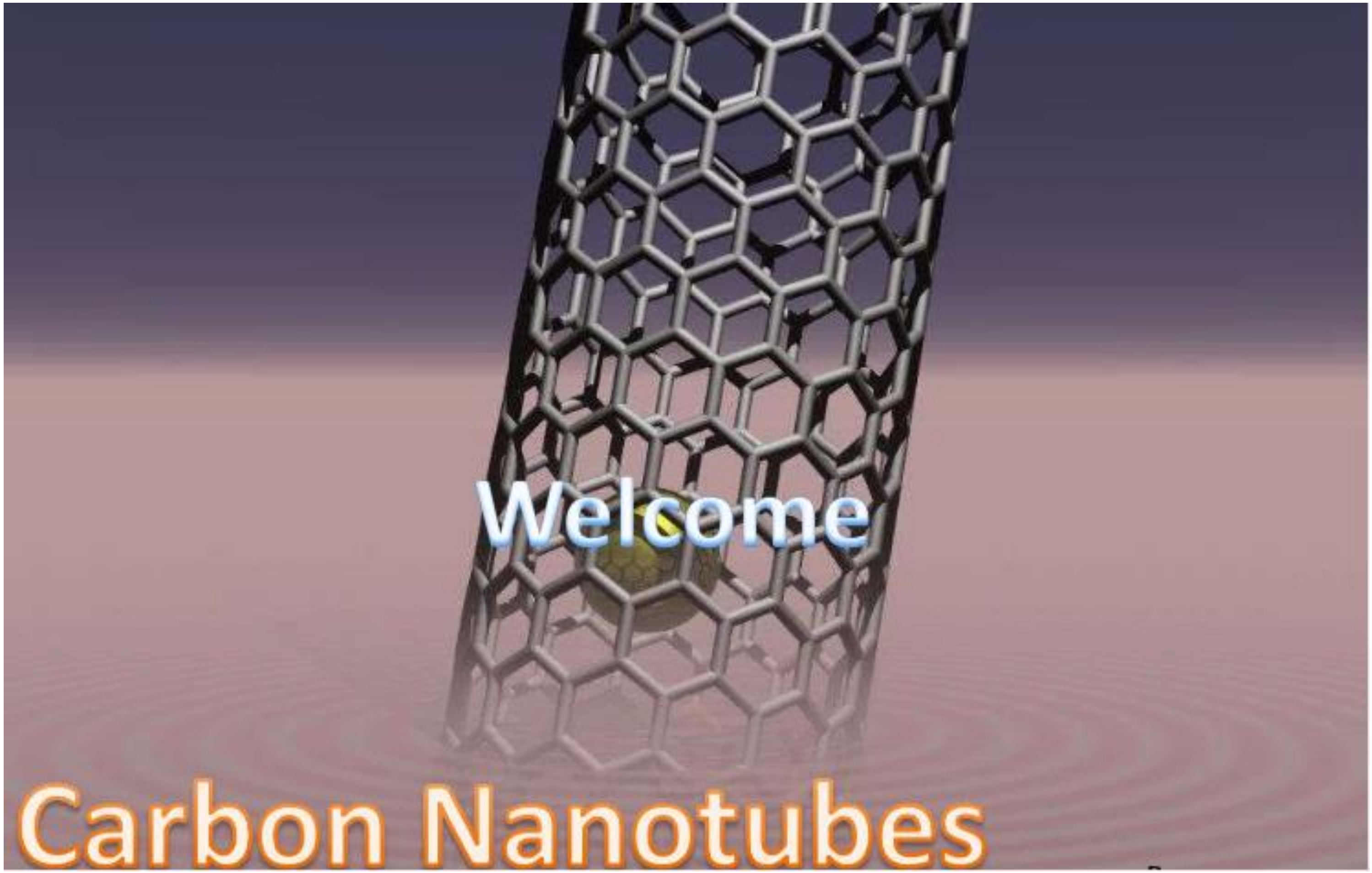
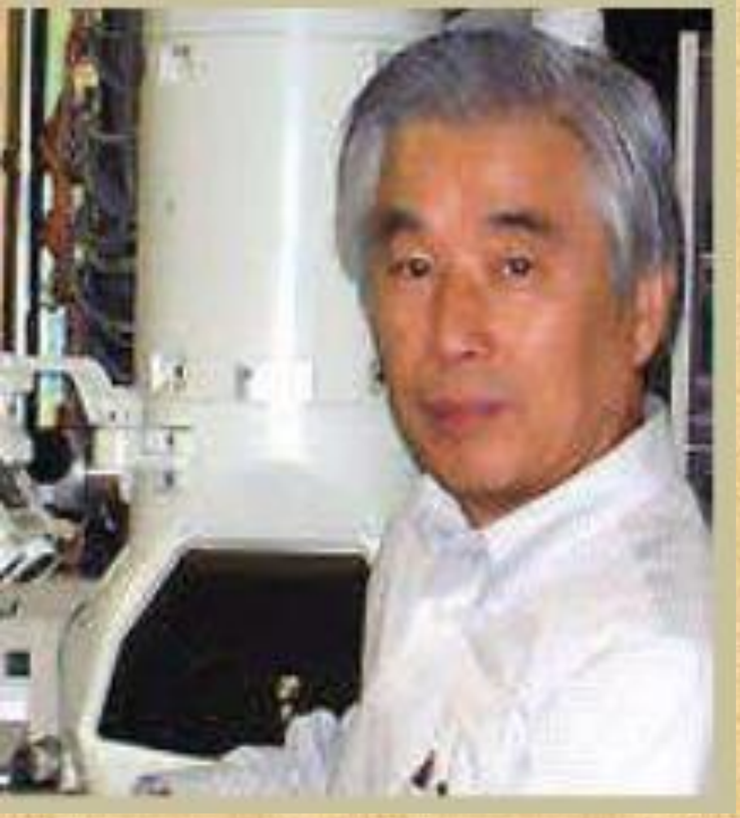


Welcome

Carbon Nanotubes

It was in 1991, Sumio Iijima of the NEC Laborato
Tsukuba used High Resolution Transmission elect
microscope to observe Carbon nanotubes, later in 1
he observed single walled carbon nanotubes.

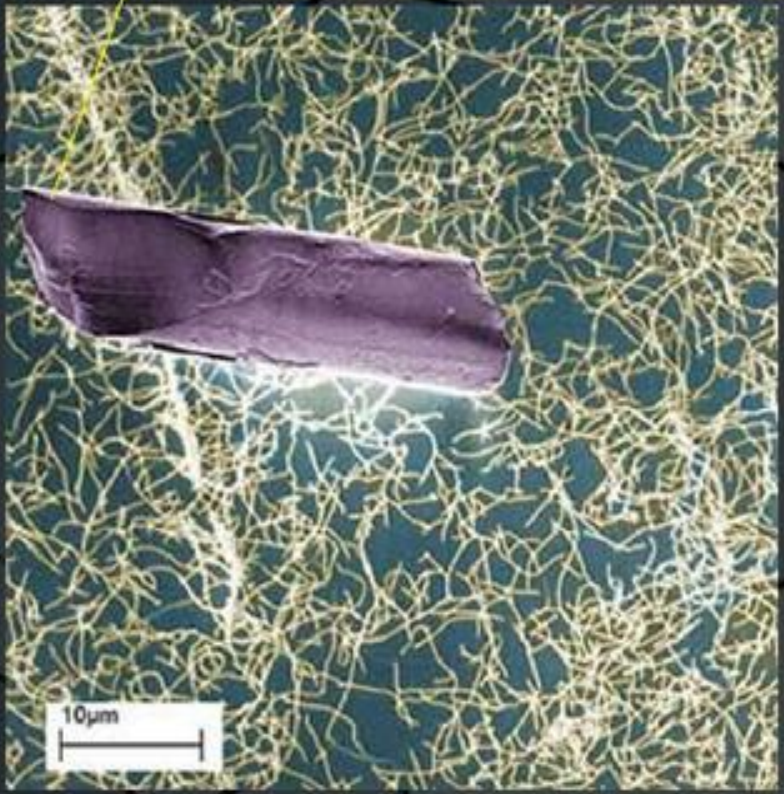
In his own words it was "<u>Serendipity</u>‟, discovery by chance



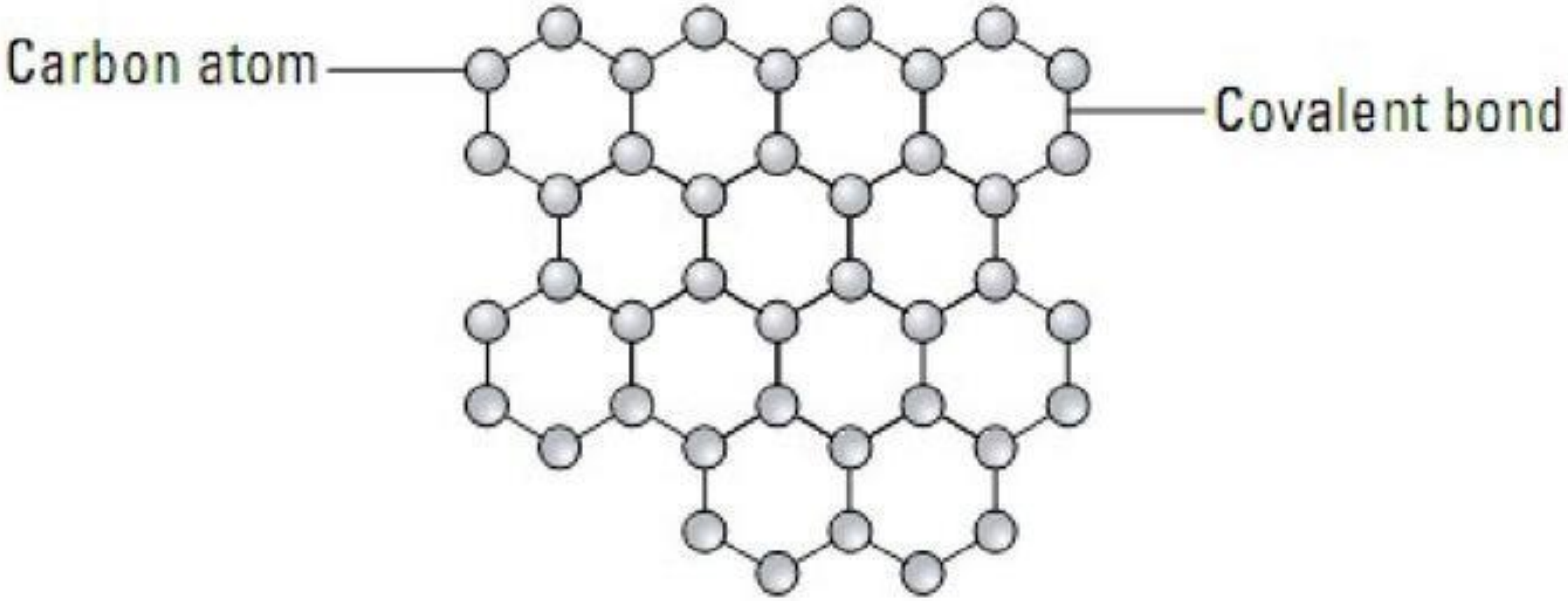
Nanotubes are members of the fullerene structural family, which also includes the spherical buckyballs. The ends of a nanotube might be capped with a hemisphere of the buckyball structure. Their name is derived from their size, since the diameter of a nanotube is on the order of a few nanometers (approximately 1/50,000th of the width of a human hair), while they can be up to 18 centimeters in length (as of 2010).

Nanotubes are categorized as single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs).

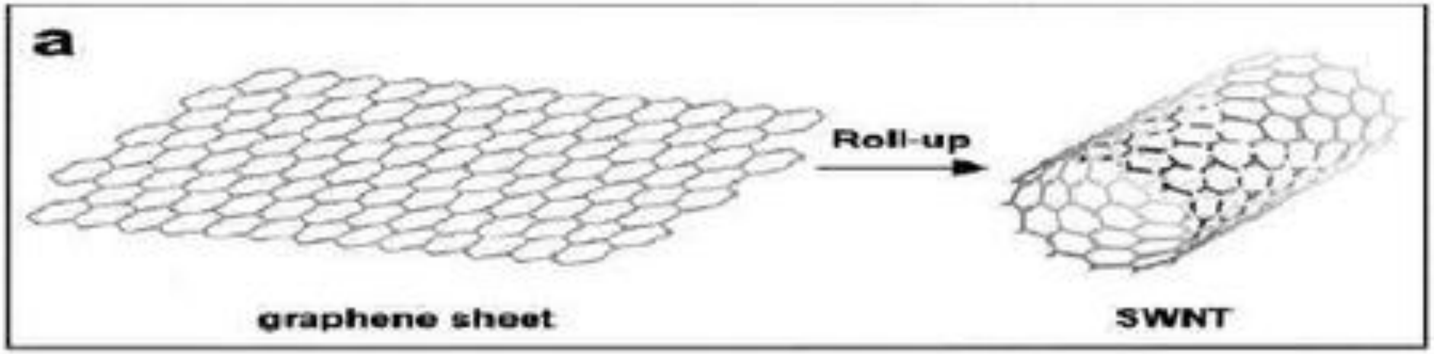
Human hair fragment (the purplish thing) on top of a network of single-walled carbon nanotubes

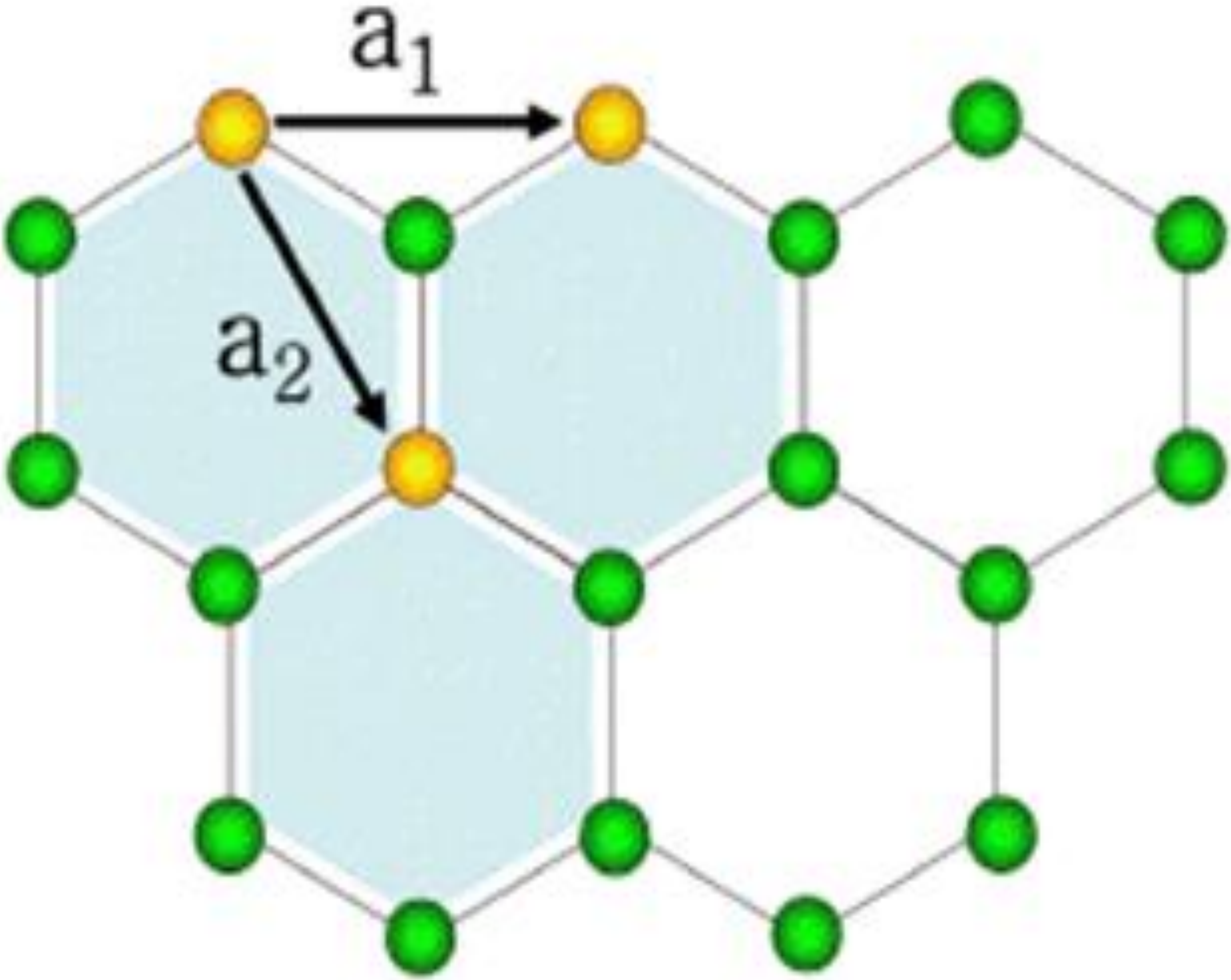


graphite



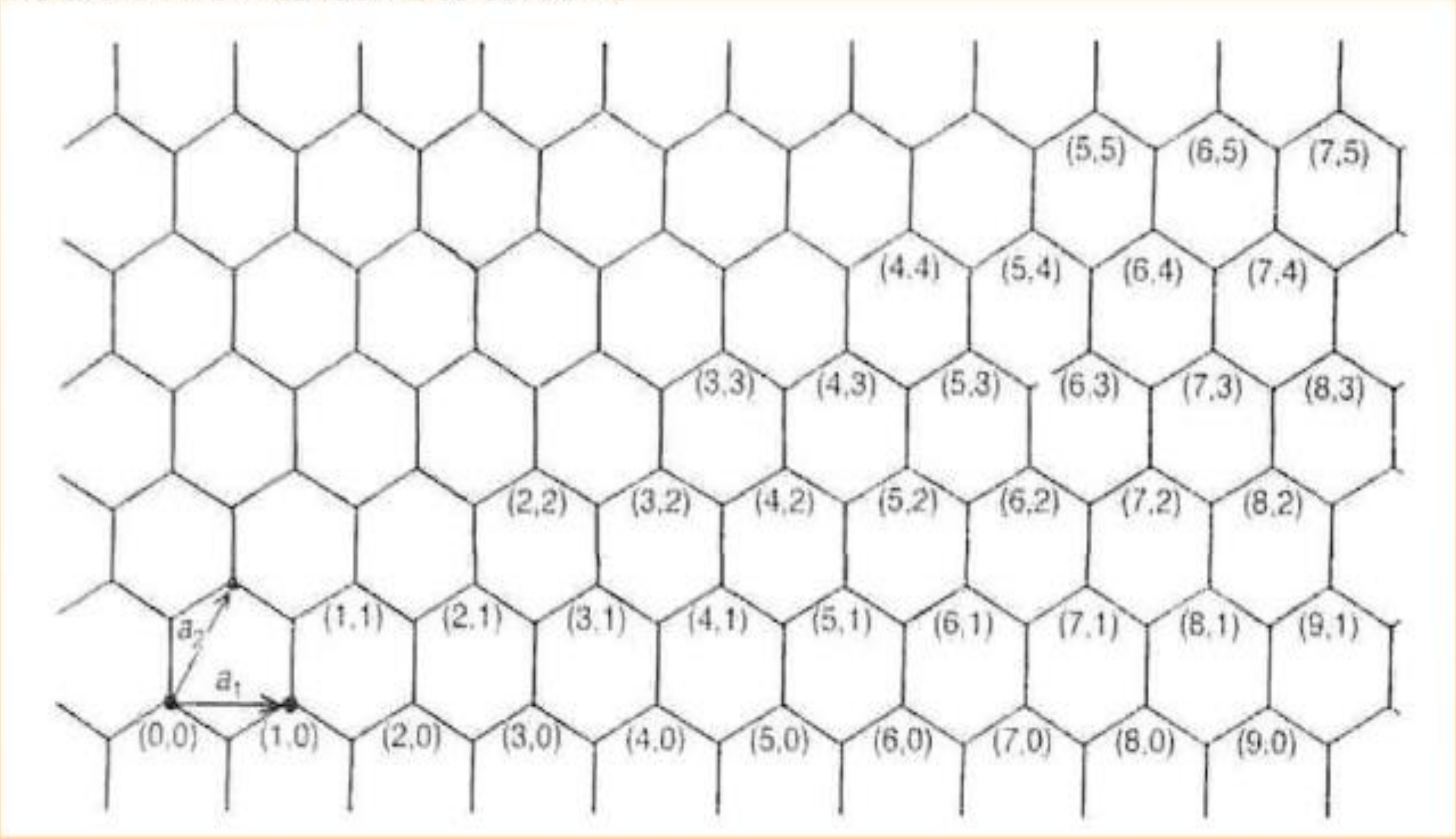
The structure of carbon atoms connected by covalent bonds in a sheet of graphite.


a
Roll-up
graphene sheet
SWNT

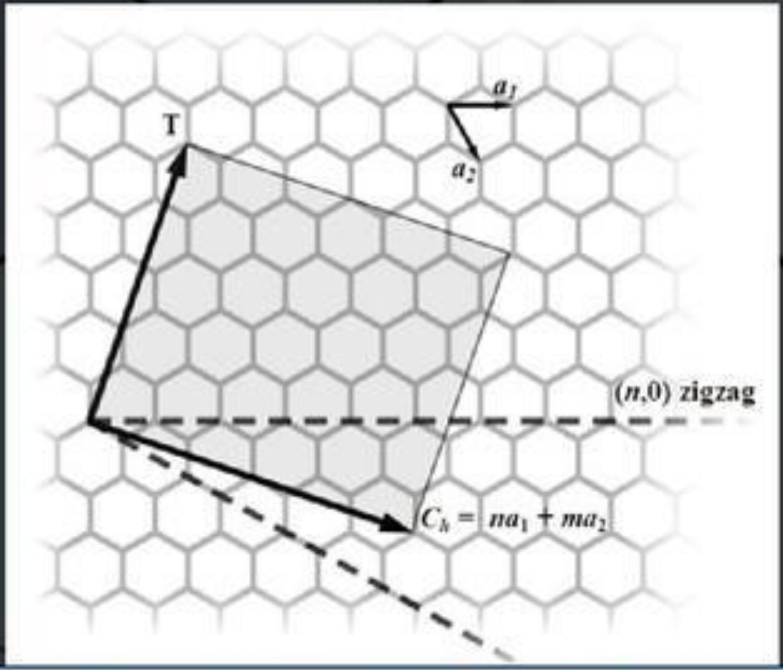

a_1
a_2

The indices refer to equally long unit vectors at 60° angles to each other across a single 6-member carbon ring.

Taking the origin as carbon number 1, the $\mathbf{a}_1$ unit vector may be considered as the line drawn from carbon 1 to carbon 3, and the $\mathbf{a}_2$ unit vector is then the line drawn from carbon 1 to carbon 5

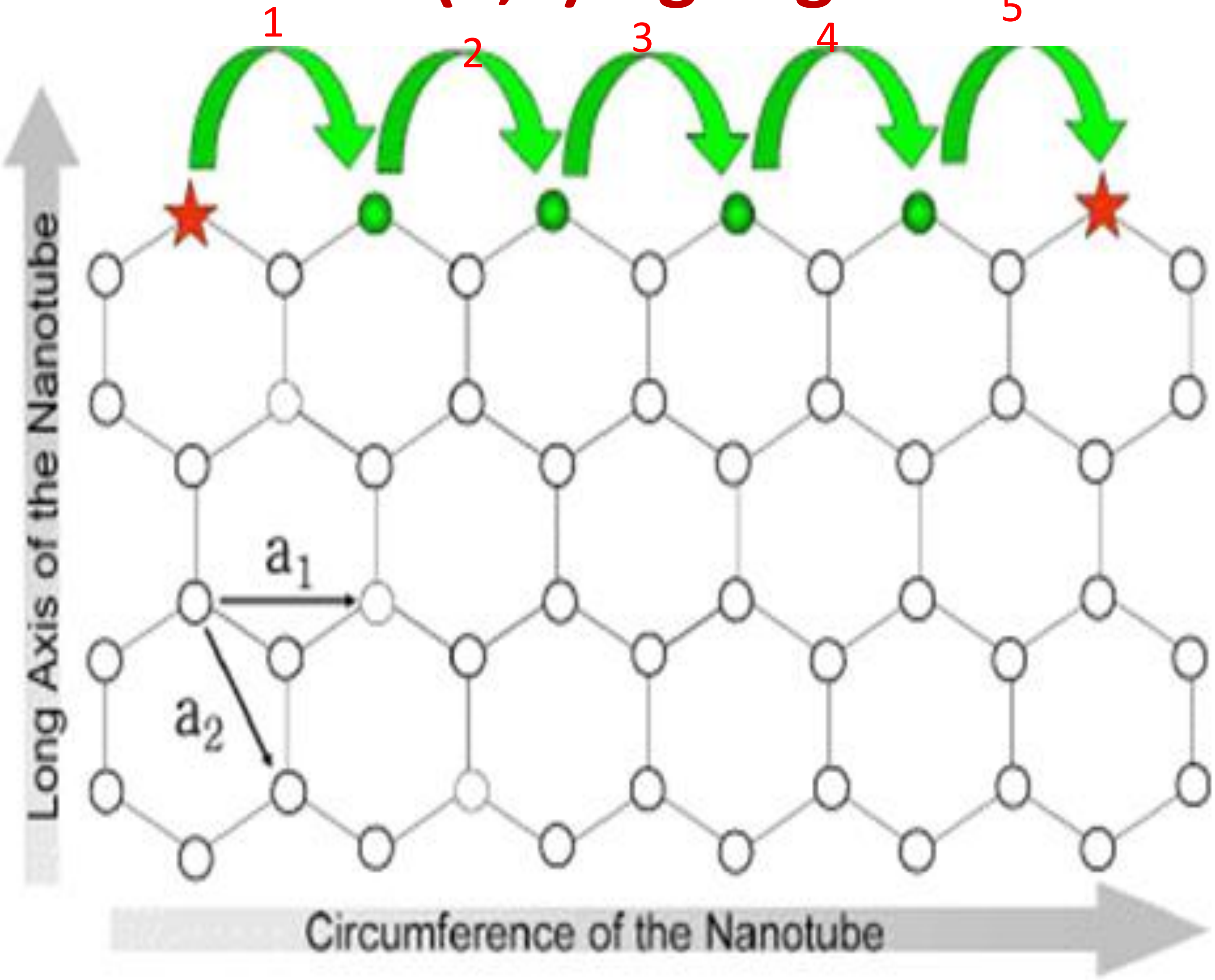


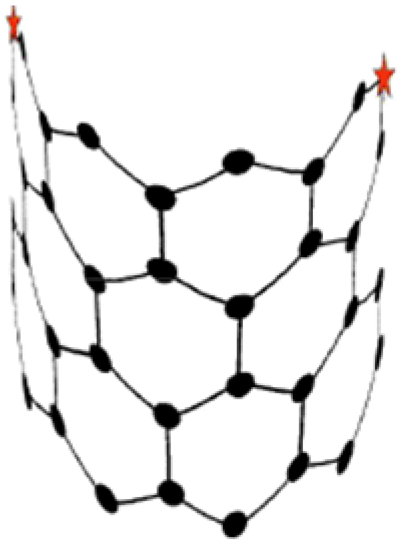
- The way the graphene sheet is wrapped is represented by a pair of indices (n,m) called the chiral vector. The integers n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. If m = 0, the nanotubes are called "zigzag". If n = m, the nanotubes are called "armchair". Otherwise, they are called "chiral".



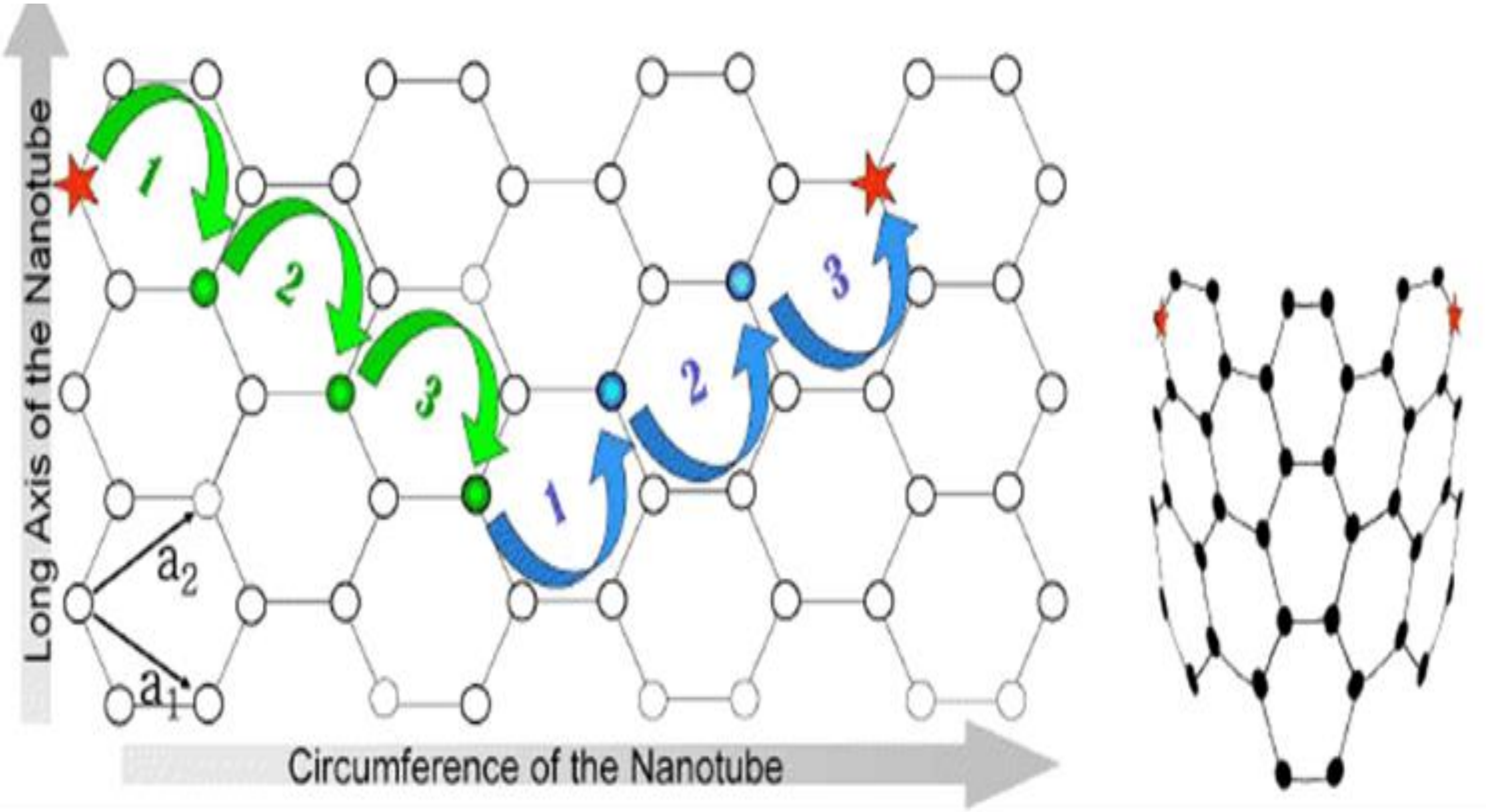
The (n,m) nanotube naming scheme can be thought of as a vector (Ch) in an infinite graphene sheet that describes how to "roll up" the graphene sheet to make the nanotube. T denotes the tube axis, and a1 and a2 are the unit vectors of graphene in real space

(5,0) zig-zag carbon nano tube

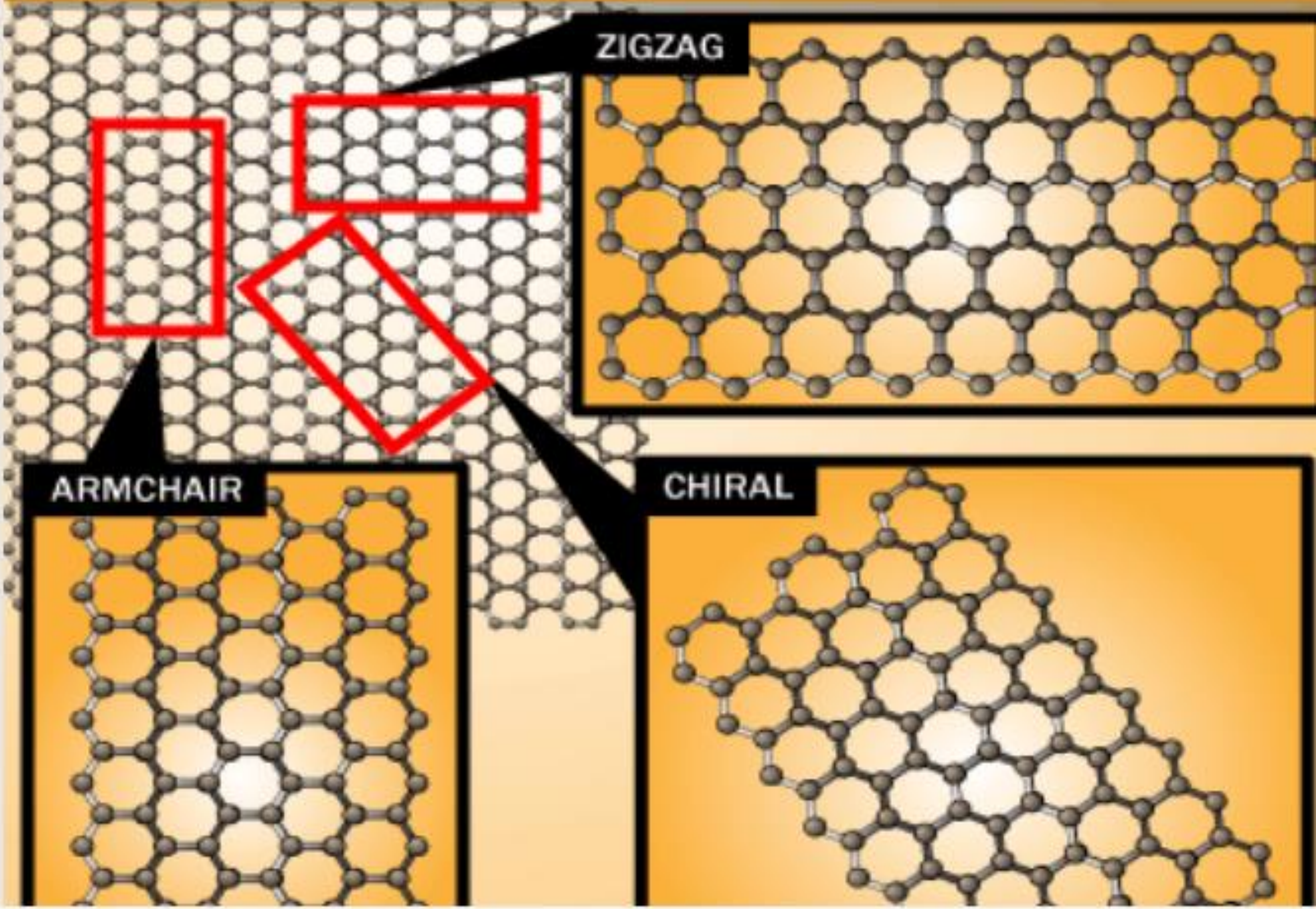




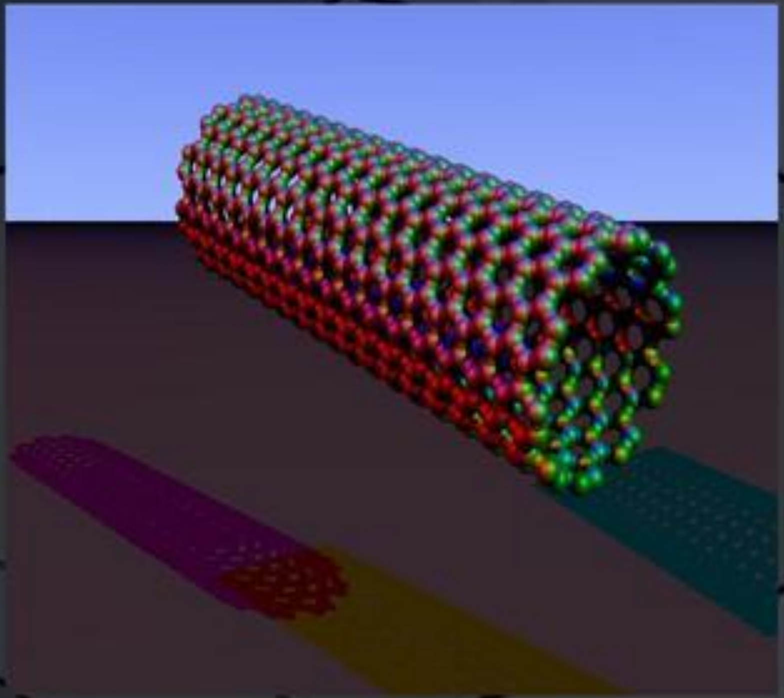
(3,3) armchair carbon nano tube



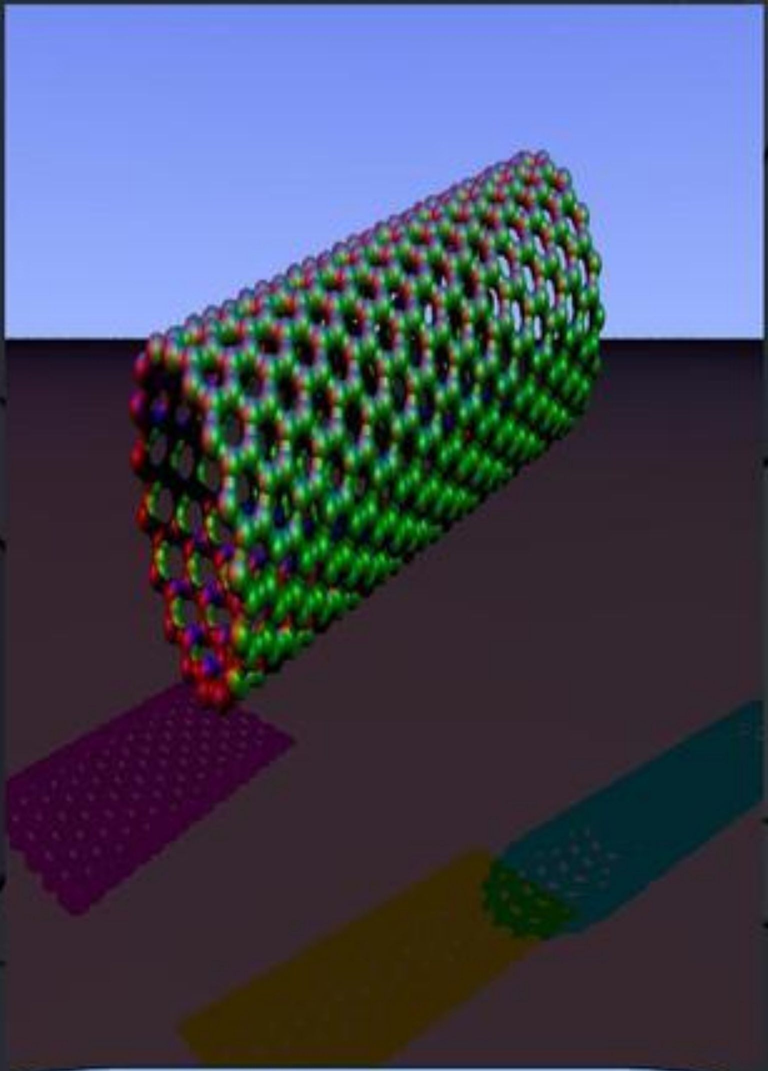
How Nanotechnology Works



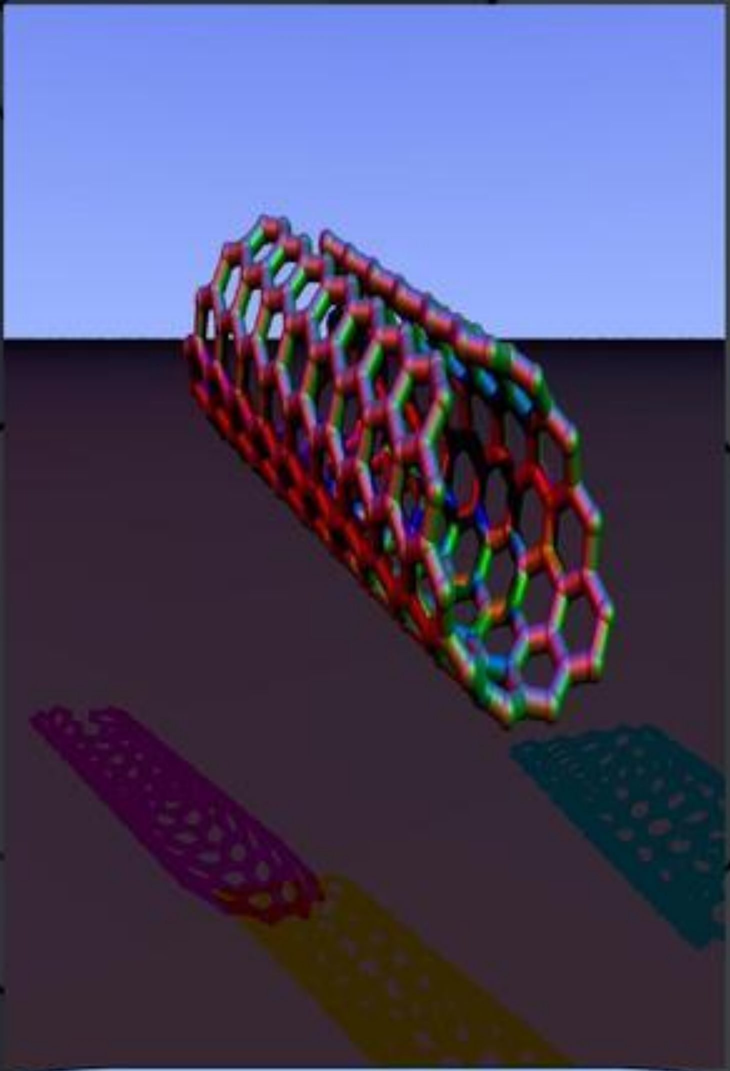
- Single-walled nanotubes are an important variety of carbon nanotube because they exhibit electric properties that are not shared by the multi-walled carbon nanotube (MWNT) variants.One useful application of SWNTs is in the development of the first intramolecular field effect transistors (FET). Production of the first intramolecular logic gate using SWNT FETs has recently become possible as well.



Armchair (n,n)



Zigzag (n,0)



Chiral (n,m)

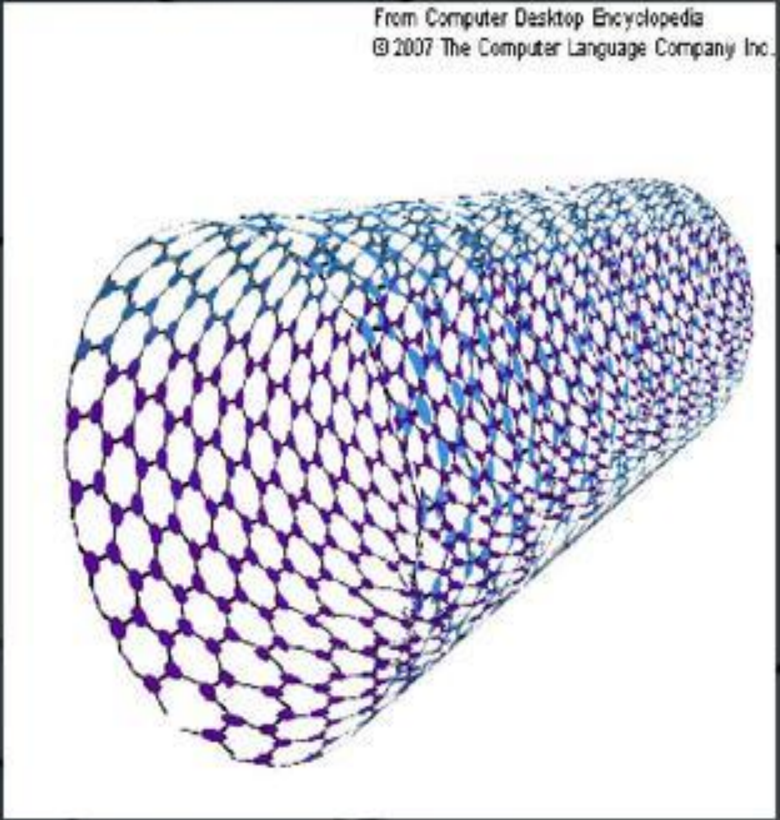
Diameter of a carbon nano tube

$$D= a/\pi(n^2+nm+m^2)^{1/2}$$

$a=0.246$ nm

Single-walled

- Most single-walled nanotubes (SWNT) have a diameter of close to 1 nanometer, with a tube length that can be many millions of times longer. The structure of a SWNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder.



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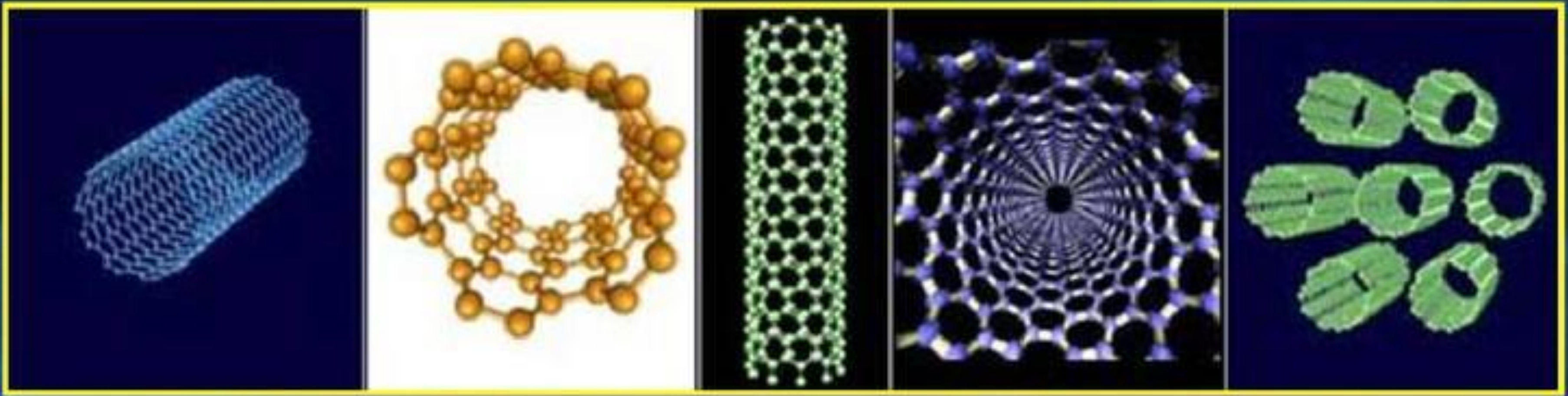
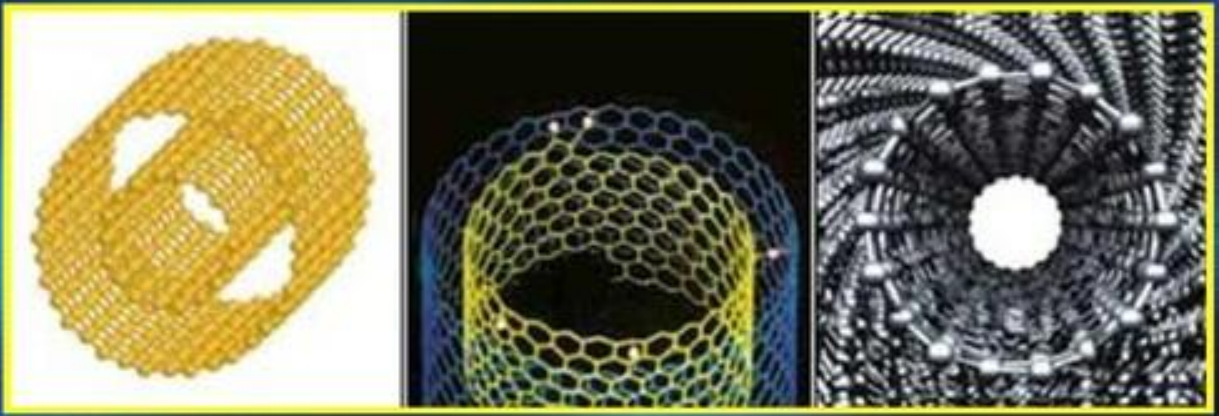
나노튜브의 종류

- **Single-walled Carbon Nanotube**

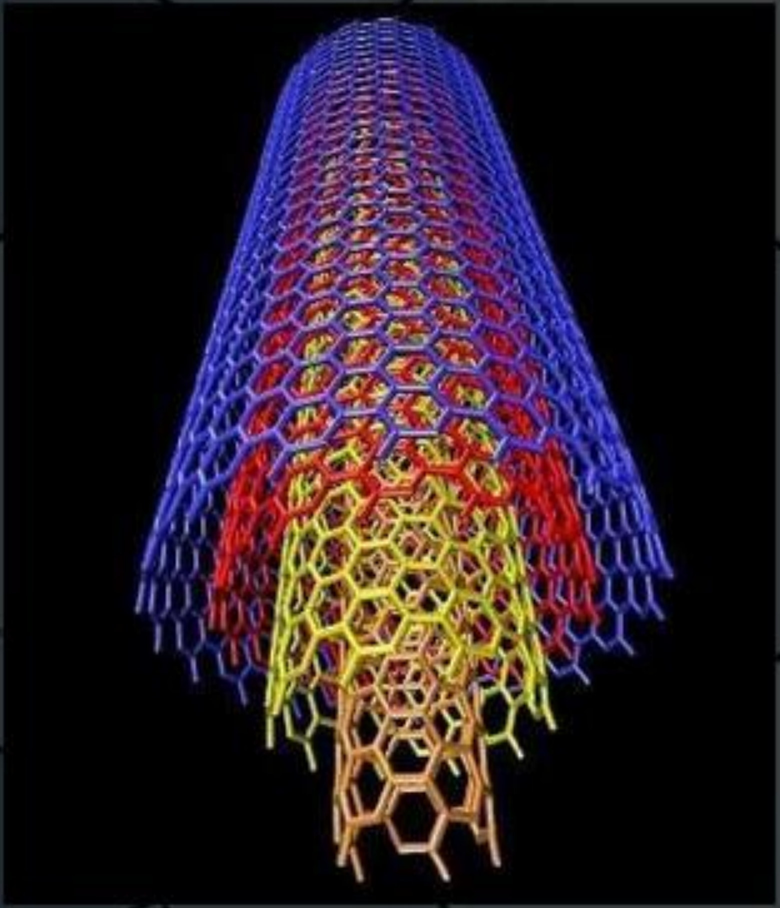


- Double-walled Carbon Nanotube



Multi-walled

- Multi-walled nanotubes (MWNT) consist of multiple rolled layers (concentric tubes) of graphite. There are two models which can be used to describe the structures of multi-walled nanotubes. In the Russian Doll model, sheets of graphite are arranged in concentric cylinders, e.g. a (0,8) single-walled nanotube (SWNT) within a larger (0,10) single-walled nanotube. In the Parchment model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å.

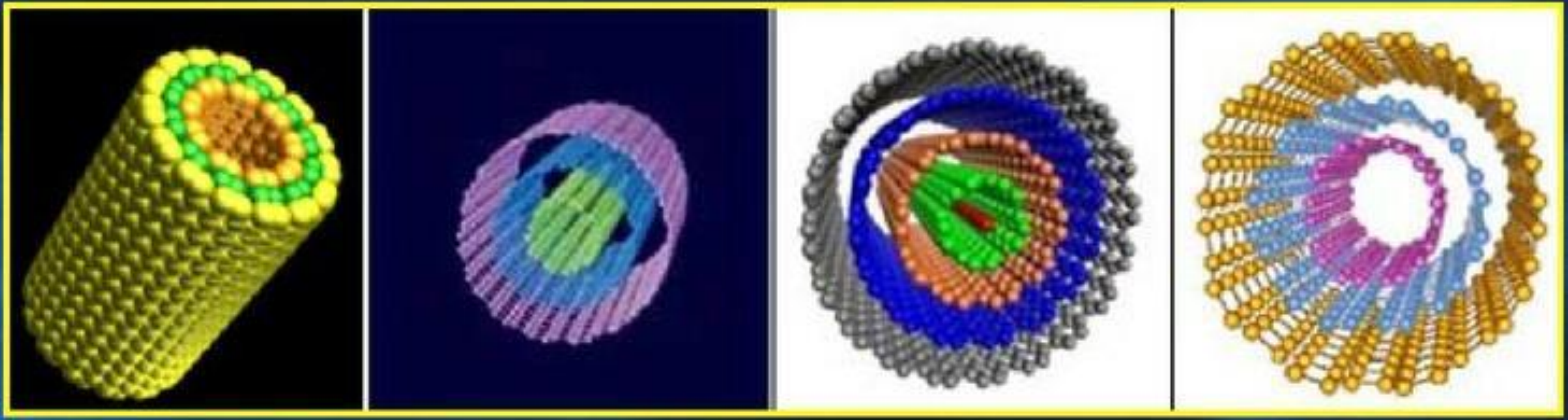


There are two types of MWNTs.They are:

1.Russian Doll model and 2. *Parchment* model

나노튜브의 종류

- Multi-walled Carbon Nanotube

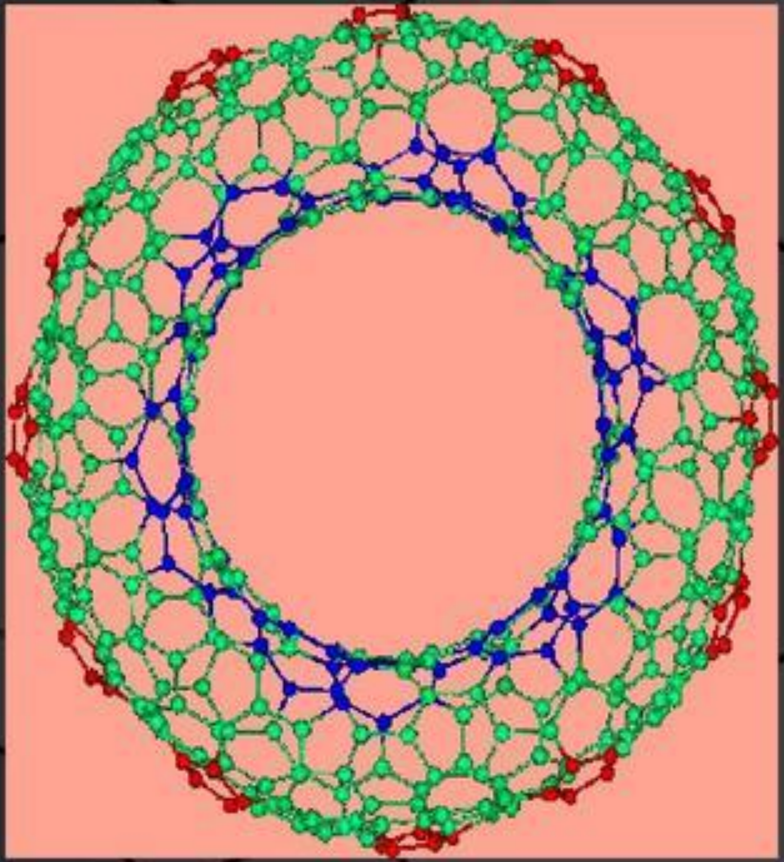


나노튜브 구조

- 흑연면이 나노 크기의 직경으로 둥글게 말린 상태로 면이 말리는 각도/구조에 따라 금속 또는 반도체 특성

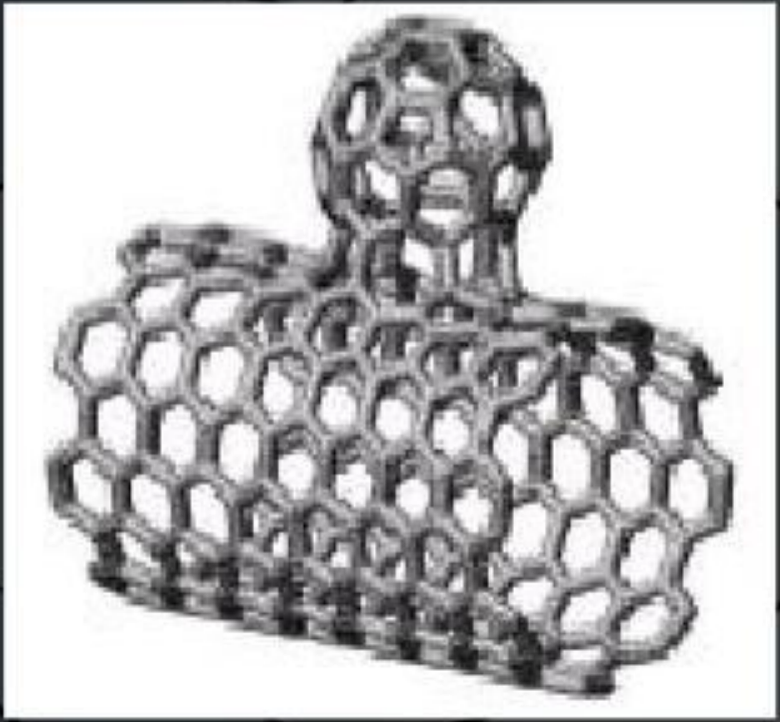
Torus

- A nanotorus is theoretically described as carbon nanotube bent into a torus (doughnut shape). Nanotori are predicted to have many unique properties, such as magnetic moments 1000 times larger than previously expected for certain specific radii.Properties such as magnetic moment, thermal stability, etc. vary widely depending on radius of the torus and radius of the tube.



Nanobud

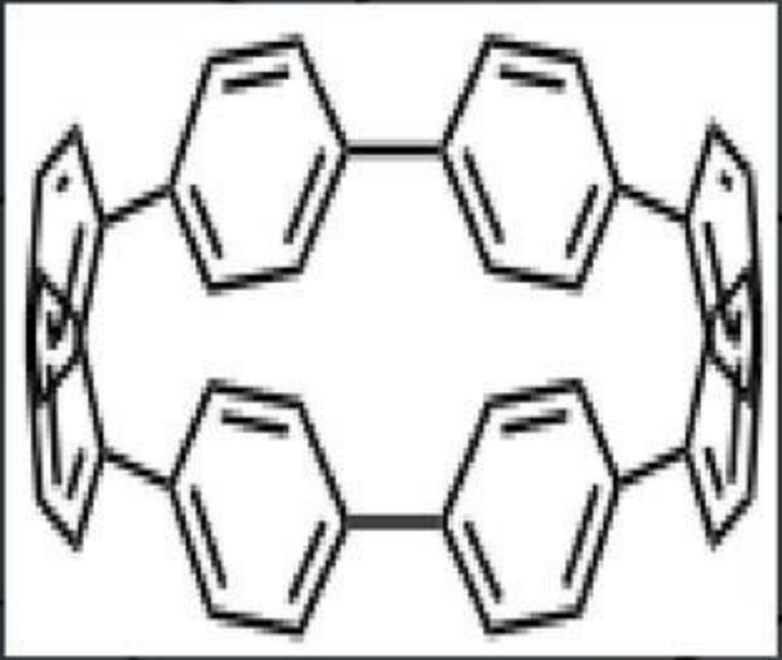
Carbon nanobuds are a newly created material combining two previously discovered allotropes of carbon: carbon nanotubes and fullerenes. In this new material, fullerene-like "buds" are covalently bonded to the outer sidewalls of the underlying carbon nanotube. This hybrid material has useful properties of both fullerenes and carbon nanotubes. In particular, they have been found to be exceptionally good field emitters. In composite materials, the attached fullerene molecules may function as molecular anchors preventing slipping of the nanotubes, thus improving the composite's mechanical properties.



A stable nanobud structure

Extreme carbon nanotubes

The observation of the longest carbon nanotubes (18.5 cm long) was reported in 2009. They were grown on Si substrates using an improved chemical vapor deposition (CVD) method and represent electrically uniform arrays of single-walled carbon nanotubes.The shortest carbon nanotube is the organic compound cycloparaphenylene which was synthesized in the early 2009. The thinnest carbon nanotube is armchair (2,2) CNT with a diameter of 3 Å.The thinnest freestanding single-walled carbon nanotube is about 4.3 Å in diameter.



Cycloparaphenylene

Synthesis: overview

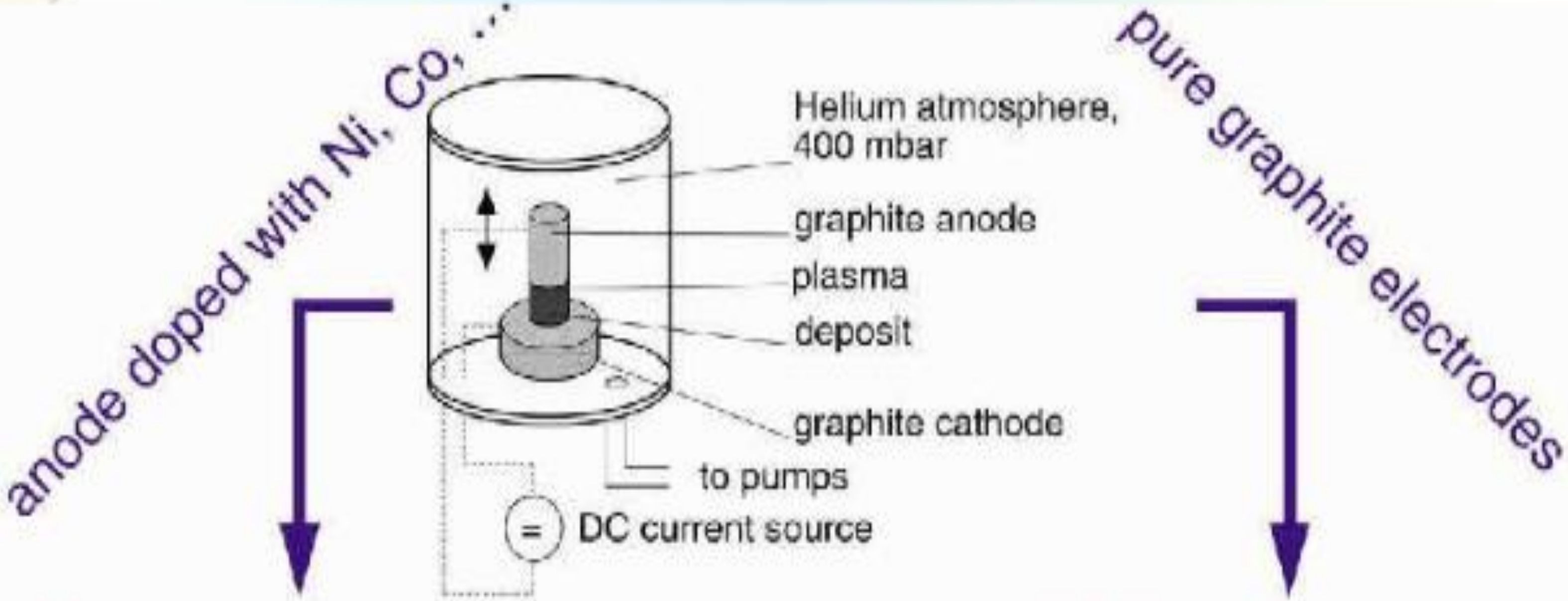
Commonly applied techniques:

- Chemical Vapor Deposition (CVD)
- Arc-Discharge
- Laser ablation

Techniques differ by:

- Type of nanotubes (SWNT / MWNT)
- Catalyst used
- Yield
- Purity

Arc discharge



anode doped with Ni, Co, ...

pure graphite electrodes

Helium atmosphere, 400 mbar

graphite anode

plasma

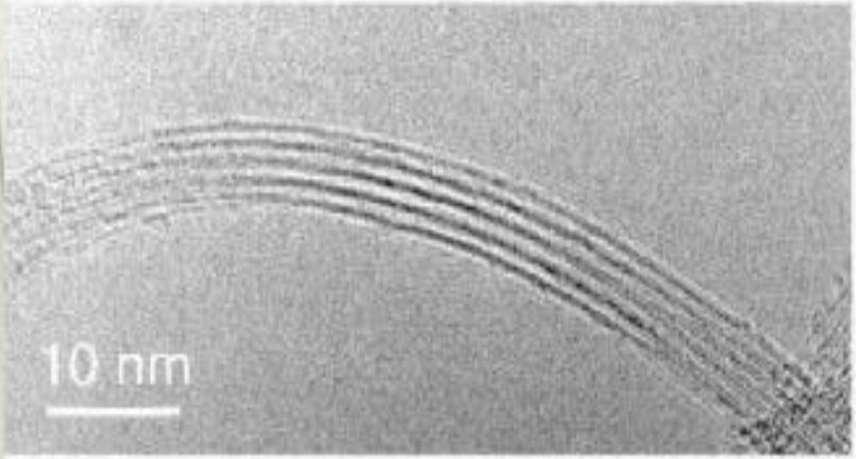
deposit

graphite cathode

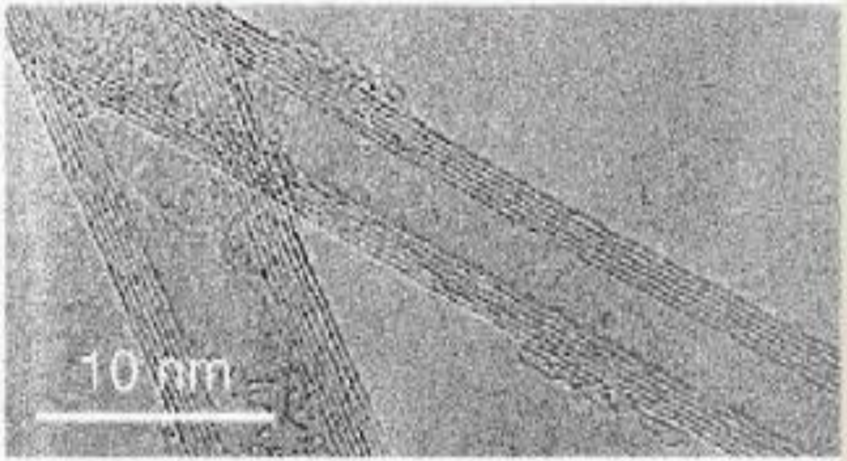
to pumps

= DC current source

Single wall nanotubes



Multiwall nanotubes



first and simplest method to synthesize Carbon Nanotubes.

Two pure graphite electrodes are connected to DC generator in atmosphere of helium.

An inert gas is added to the chamber which does not react with carbon.

Electric current is run thorough electrodes and therefore Carbon is deposited into cathode from anode and CNT are shaped in the middle .

quite perfect about few micro meters long

inner tube is 1-3 nm and outer tube in MWNT 10 nm in diameter.

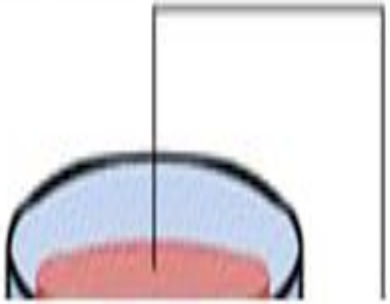
Drawback

If both of the electrodes are made of graphite (mixture of CNTs along with fullerene, sheets of graphite, amorphous carbon)

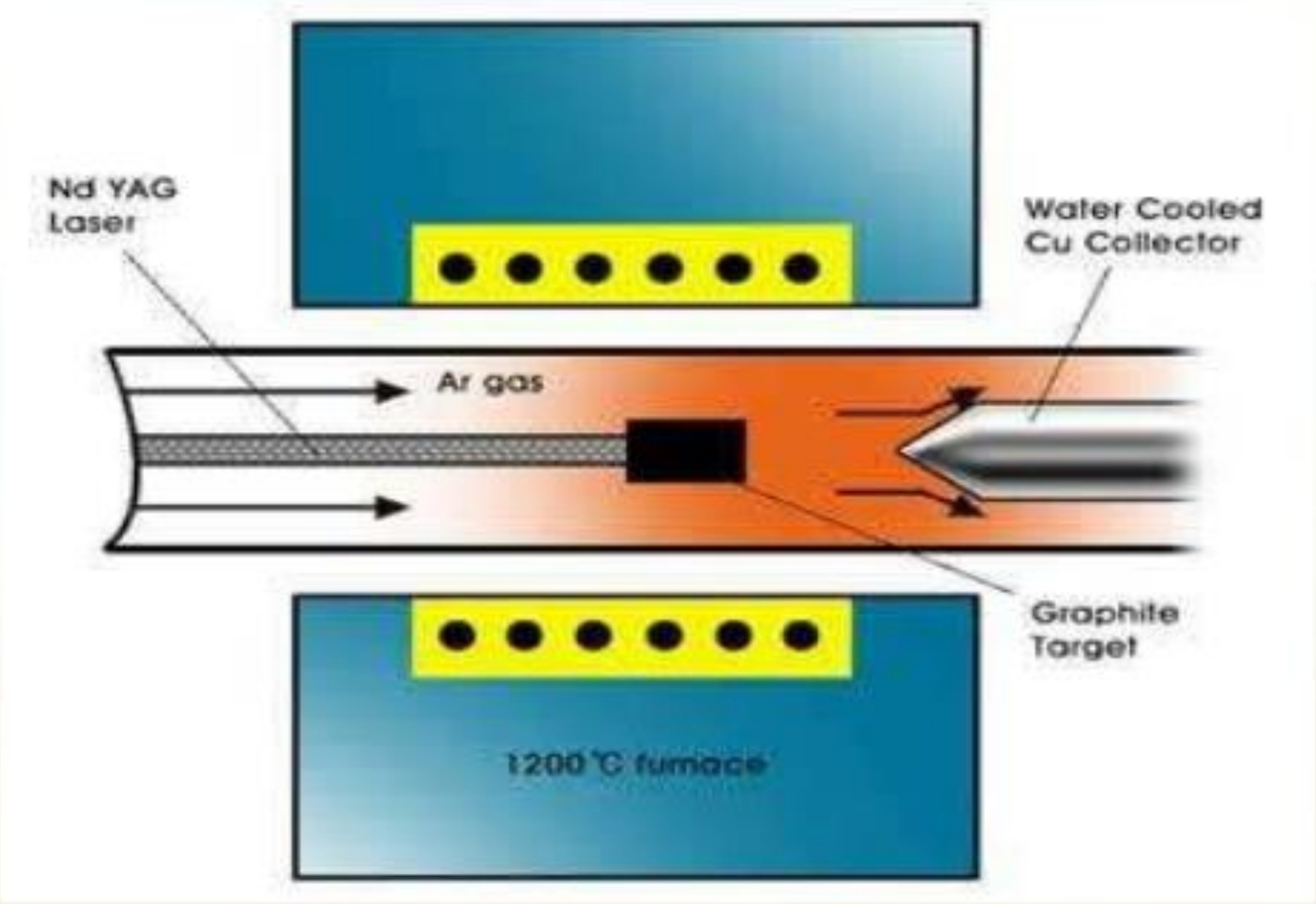
more work to separate CNTs from its undesirable by-products.

4000 °C which is an extremely high temperature .

Electric arc method good for scientific study but not for industrial use .



Synthesis: laser ablation



Laser ablation

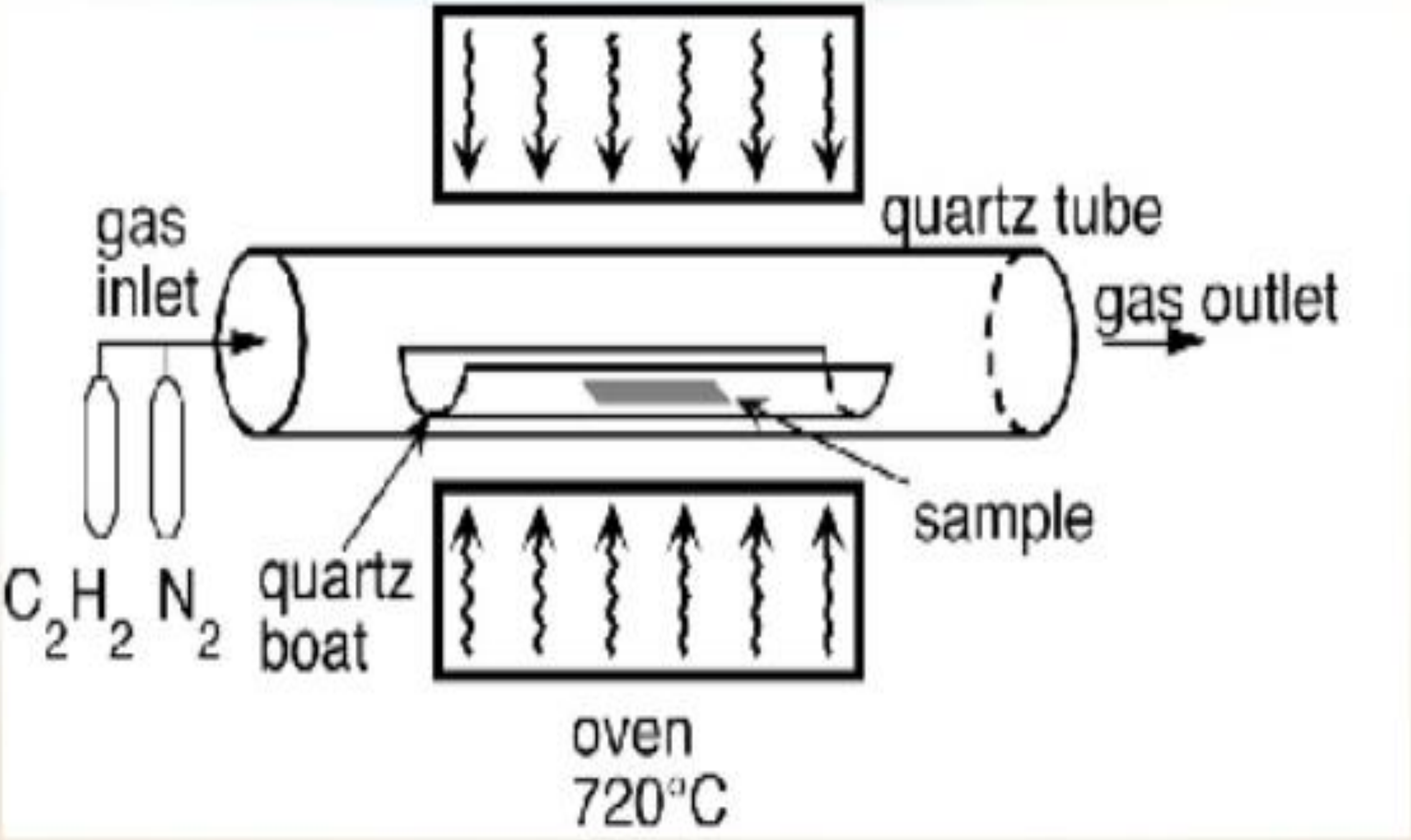
In the laser ablation process, a pulsed laser vaporizes a graphite target in a high-temperature reactor while an inert gas is bled into the chamber.

Nanotubes develop on the cooler surfaces of the reactor as the vaporized carbon condenses.

A water-cooled surface may be included in the system to collect the nanotubes.

The laser ablation method yields around 70% and produces primarily single-walled carbon nanotubes.

Synthesis:
CVD



chemical-vapor deposition, or CVD

- In this method, a hydrocarbon — say, methane gas (one carbon atom and four hydrogen atoms) — flows into a heated chamber containing a substrate coated with a catalyst, such as iron particles. The temperature in the chamber is high enough to break the bonds between the carbon atoms and the hydrogen atoms in the methane molecules — resulting in carbon atoms with no hydrogen atoms attached. Those carbon atoms attach to the catalyst particles, where they bond to other carbon atoms — forming a nanotube.

Chemical vapor deposition (CVD)

During CVD, a substrate is prepared with a layer of metal catalyst particles, most commonly nickel, cobalt, iron, or a combination

The diameters of the nanotubes that are to be grown are related to the size of the metal particles.

The substrate is heated to approximately 700°C.
To initiate the growth of nanotubes, two gases are bled into the reactor: a process gas (such as ammonia, nitrogen or hydrogen) and a carbon-containing gas (such as acetylene, ethylene, ethanol or methane).

Nanotubes grow at the sites of the metal catalyst; the carbon-containing gas is broken apart at the surface of the catalyst particle, and the carbon is transported to the edges of the particle, where it forms the nanotubes.

plasma process

- A brand-new method uses a plasma process to produce nanotubes. Methane gas, used as the source of carbon, is passed through a plasma torch. Nobody’s revealed the details of this process yet, such as what, if any, catalyst is used. One of the initial claims is that this process is 25 times more efficient at producing nanotubes than the other two methods.

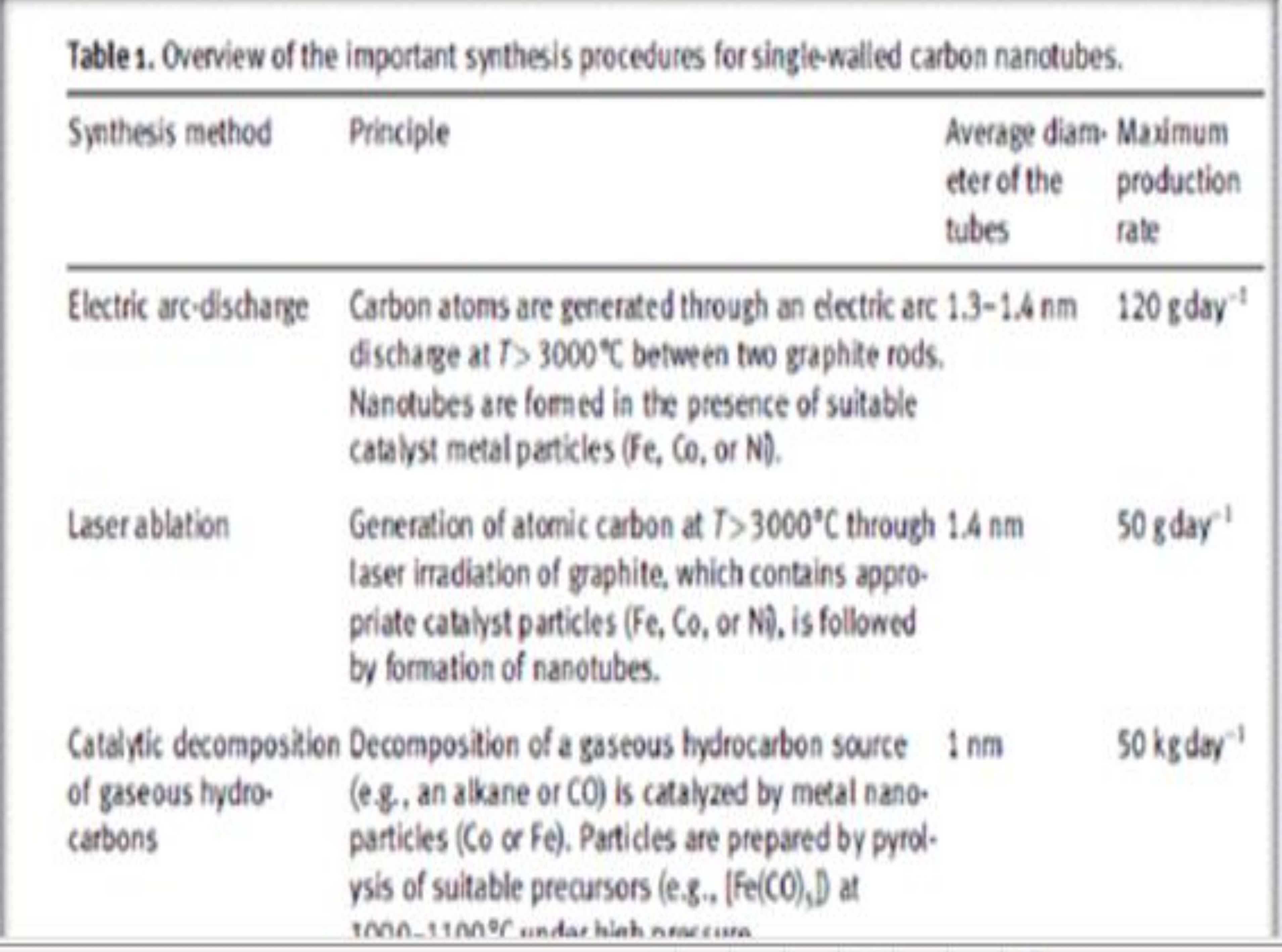
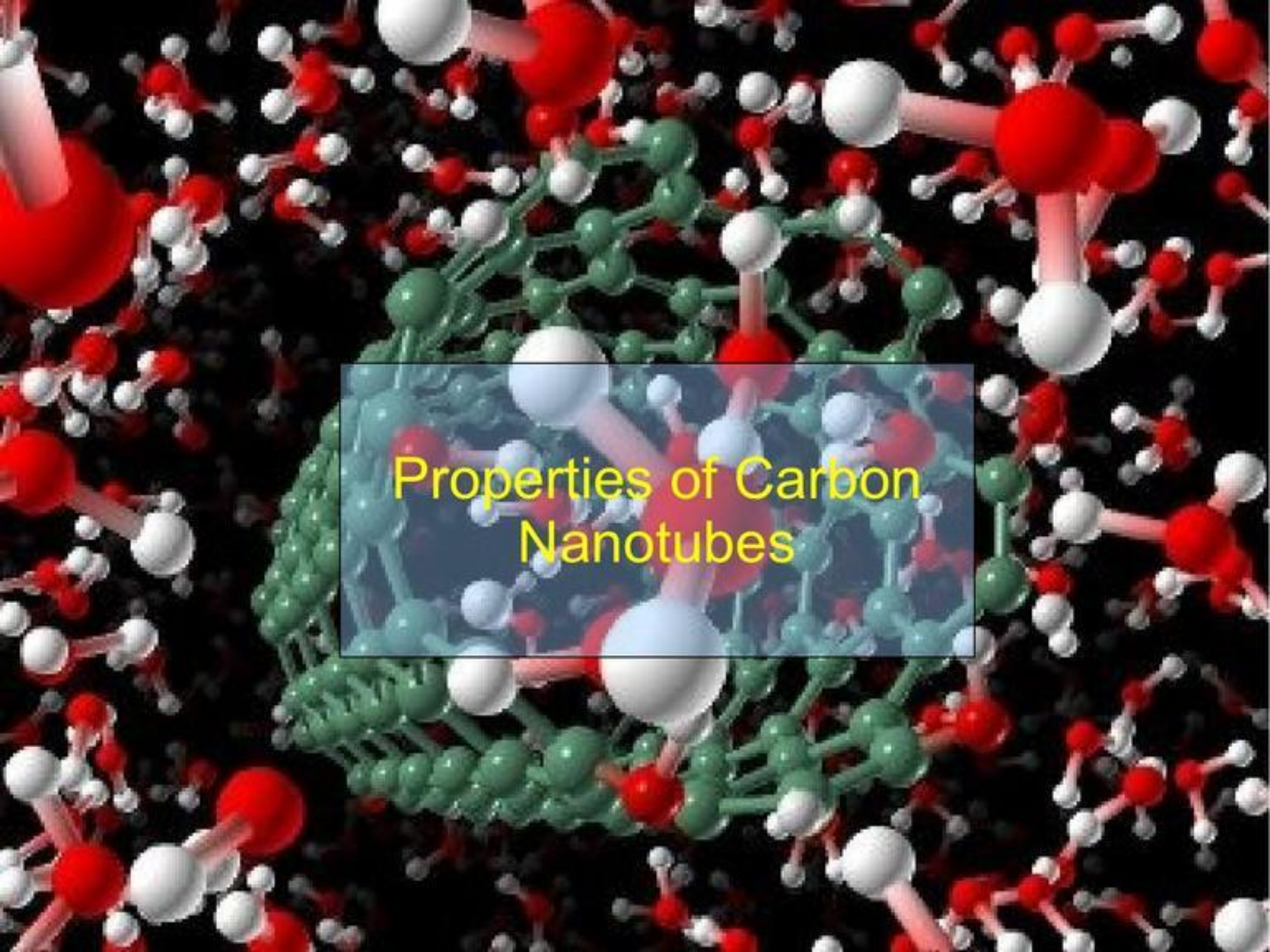


Table 1. Overview of the important synthesis procedures for single-walled carbon nanotubes.

Synthesis method	Principle	Average diameter of the tubes	Maximum production rate
Electric arc-discharge	Carbon atoms are generated through an electric arc discharge at $T > 3000\,^{\circ}\mathrm{C}$ between two graphite rods. Nanotubes are formed in the presence of suitable catalyst metal particles (Fe, Co, or Ni).	1.3–1.4 nm	120 g day^{-1}
Laser ablation	Generation of atomic carbon at $T > 3000\,^{\circ}\mathrm{C}$ through laser irradiation of graphite, which contains appropriate catalyst particles (Fe, Co, or Ni), is followed by formation of nanotubes.	1.4 nm	50 g day^{-1}
Catalytic decomposition of gaseous hydrocarbons	Decomposition of a gaseous hydrocarbon source (e.g., an alkane or CO) is catalyzed by metal nanoparticles (Co or Fe). Particles are prepared by pyrolysis of suitable precursors (e.g., $[\mathrm{Fe(CO)_5}]$) at 1000–1100 °C under high pressure.	1 nm	50 kg day^{-1}



Properties of Carbon Nanotubes

- CNTs have High Electrical Conductivity
- CNTs have Very High Tensile Strength
- CNT are Highly Flexible- can be bent considerably without damage
- CNTs are Very Elastic ~18% elongation to failure
- CNTs have High Thermal Conductivity
- CNTs have a Low Thermal Expansion Coefficient
- CNTs are Good Electron Field Emitters
- CNTs have a High Aspect Ratio (length = ~1000 x diameter

Strength

- Carbon nanotubes are the strongest and stiffest materials yet discovered in terms of tensile strength and elastic modulus respectively. This strength results from the covalent sp2 bonds formed between the individual carbon atoms. In 2000, a multi-walled carbon nanotube was tested to have a tensile strength of 63 gigapascals (GPa). (This, for illustration, translates into the ability to endure tension of a weight equivalent to 6422 kg on a cable with cross-section of 1 mm2.) Since carbon nanotubes have a low density for a solid of 1.3 to 1.4 g·cm−3, its specific strength of up to 48,000 kN·m·kg−1 is the best of known materials, compared to high-carbon steel's 154 kN·m·kg−1. CNTs are not nearly as strong under compression. Because of their hollow structure and high aspect ratio, they tend to undergo buckling when placed under compressive, torsional or bending stress.

Comparison of mechanical properties

Material	Young's modulus (TPa)	Tensile strength (GPa)	Elongation at break (%)
SWNT	~1 (from 1 to 5)	13–53	16
Armchair SWNT	0.94	126.2	23.1
Zigzag SWNT	0.94	94.5	15.6-17.5
Chiral SWNT	0.92		
MWNT	0.27-0.8--0.95	11-63-150	
Stainless steel	0.186-0.214	0.38-1.55	15-50
Kevlar–29&149	0.06-0.18	3.6-3.8	~2

Hardness

- Diamond is considered to be the hardest material, and it is well known that graphite transforms into diamond under conditions of high temperature and high pressure. One study succeeded in the synthesis of a super-hard material by compressing SWNTs to above 24 GPa at room temperature. The hardness of this material was measured with a nanoindenter as 62–152 GPa. The hardness of reference diamond and boron nitride samples was 150 and 62 GPa, respectively. The bulk modulus of compressed SWNTs was 462–546 GPa, surpassing the value of 420 GPa for diamond.

Kinetic property

- Multi-walled nanotubes, multiple concentric nanotubes precisely nested within one another, exhibit a striking telescoping property whereby an inner nanotube core may slide, almost without friction, within its outer nanotube shell thus creating an atomically perfect linear or rotational bearing. This is one of the first true examples of molecular nanotechnology, the precise positioning of atoms to create useful machines. Already this property has been utilized to create the world's smallest rotational motor

Electrical property

- Because of the symmetry and unique electronic structure of graphene, the structure of a nanotube strongly affects its electrical properties. For a given (n,m) nanotube, if n = m, the nanotube is metallic; if n − m is a multiple of 3, then the nanotube is semiconducting with a very small band gap, otherwise the nanotube is a moderate semiconductor. Thus all armchair (n = m) nanotubes are metallic, and nanotubes (6,4), (9,1) etc. are semiconducting.

Thermal property

- All nanotubes are expected to be very good thermal conductors along the tube, exhibiting a property known as "ballistic conduction," but good insulators laterally to the tube axis. Measurements show that a SWNT has a room-temperature thermal conductivity along its axis of about 3500 W·m−1·K−1;compare this to copper, a metal well-known for its good thermal conductivity, which transmits 385 W·m−1·K−1. A SWNT has a room-temperature thermal conductivity across its axis of about 1.52 W·m−1·K−1,

CHEMICAL FUNCTIONALIZATION

1. ENDOHEDRAL
2. EXOHEDRAL

Endohedral Functionalization

Modification of CNT by putting nanoparticles inside the tube.

Change the hydrophobic structure to hydrophilic and make them as solvents.

Filling Nanotubes with nanoparticles to add the characteristics of the Nanoparticles inside the Carbon Nanotubes to fantastic phenomenal of CNT.

1.Putting CNT inside the suspension **containing nanoparticles so that it can penetrate** the tube internal site

and stay inside the CNT

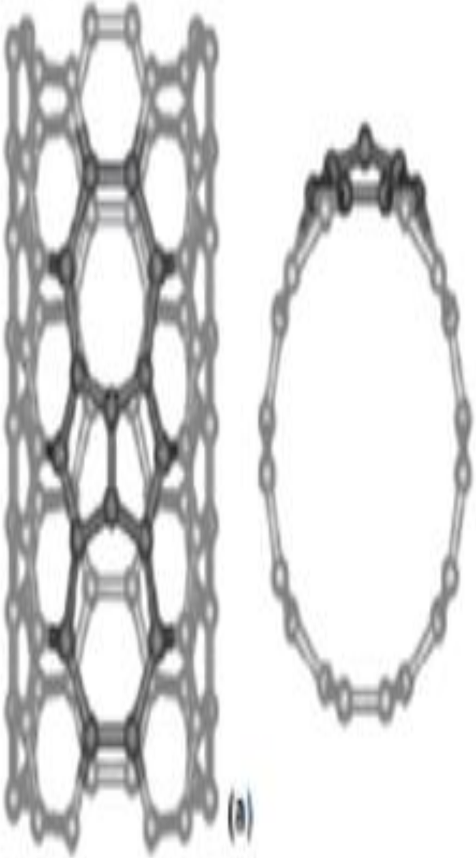
Depends on surface energy(surface tension) of the liquid.

Experiments show that if surface tension of the liquid is more than 200 mN/m, liquid can fill the Nanotubes

2. Are filled with a material **which reacts with it and then produces nanoparticles which are trapped**

Exohedral Functionalization

Exohedral Functionalization is modification of external part of CNTs like side walls .



This method itself is subcategorized into three main methods :

1.Covalent Exohedral functionalization-Defects

defect in CNT = best place for functionalization.

(Stone wall)

2.Covalent Exohedral functionalization -Functional groups

Side wall functionalization & to attach more functionalized group.

3.Noncovalent exohedral functionalization- Polymer wrapping

wrapping CNT in polymer, surfactants and peptides (smaller amino acids in length).

By wrapping the polymer around the CNT there is a phenomena called Pi stacking.

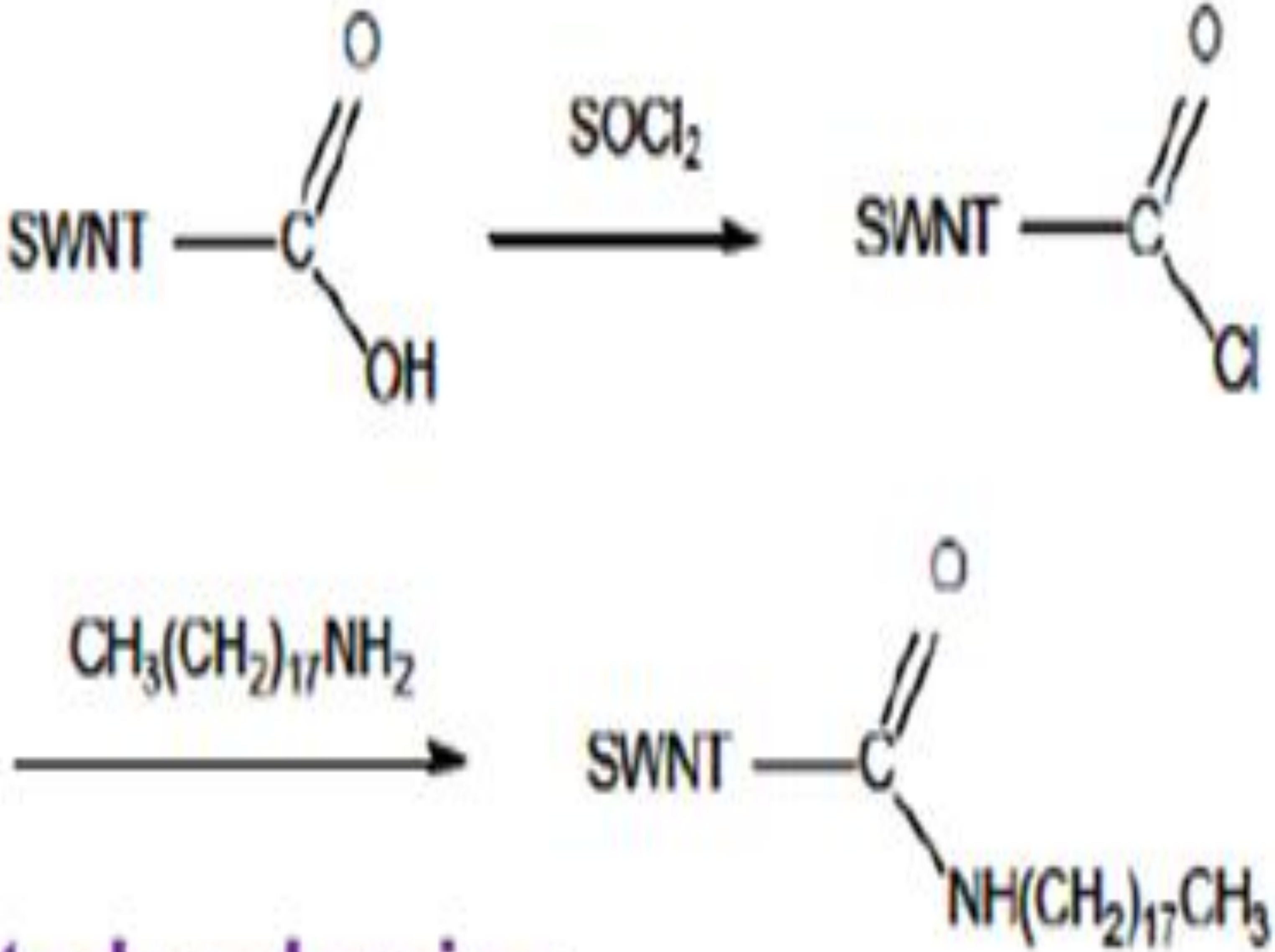
Pi stacking is when the P orbitals of CNT and functionalized group interact with each other and cause less stability.

In this type of functionalization electrical and optical properties of CNTs are not damaged and perturbed but because of poor interaction of p orbitals, stability is quite low .

As experiments show there is an improved electrical property of the polymer

1. **Amidation – Formation of Carbon Nanotube-Acyl Amides**
2. **Fluorination of Nanotubes**
3. Chlorination of Carbon Nanotubes
4. Bromination of MWCNTs
5. Hydrogenation of Carbon Nanotubes.
6. Addition of Radicals
7. Addition of Nucleophilic Carbenes
8. Sidewall Functionalization through Electrophilic Addition
9. Addition of Nitrenes
10. Nucleophilic Cyclopropanation

11. Azomethine Ylides .
12. Diels-Alder Reaction
13. Sidewall Osmylation of Individual SWCNTs
14. Aryl Diazonium Chemistry –
15. Electrochemical Functionalization
16. Cathodic Coupling
17. Anodic Coupling

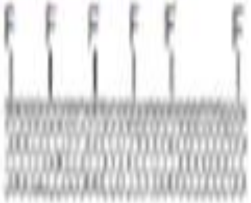

SWNT
O
C
OH
SOCl2
SWNT
O
C
Cl
CH3(CH2)17NH2
SWNT
O
C
NH(CH2)17CH3

This process can be done on already functionalized CNTs by carboxyl group then they can be functionalized by fluorine .

further functionalization meaning that we can remove the fluorine and attach other functional groups.

This process can be continues by removing fluorine and replacing it with other functional group .

By this process there will be no damage imposed to CNT sidewalls and temperature is low about 150 °C to 500 °C. In this case for maximum fluorination can be achieved using iodine **pentafluoride IF_5**, which leads to composition of C-F bonds .



APPLICATIONS

- AFM PROBE TIPS
- FLAT PANEL DISPLAY SCREENS
- NANO COMPOSITES
- ACTUATOR/ARTIFICIAL MUSCLE
- HYDROGEN STORAGE
- SENSORS
- ELECTRONICS

- A carbon nanotube is a Nano-size cylinder of carbon atoms.
- Imagine a sheet of carbon atoms, which would look like a sheet of hexagons. If you roll that sheet into a tube, you'd have a carbon nanotube.
- Carbon nanotube properties depend on how you roll the sheet.
- In other words, even though all carbon nanotubes are made of carbon, they can be very different from one another based on how you align the individual atoms.
- With the right arrangement of atoms, you can create a carbon nanotube that's hundreds of times stronger than steel, but six times lighter
- Engineers plan to make building material out of carbon nanotubes, particularly for things like cars and airplanes.
- Lighter vehicles would mean better fuel efficiency, and the added strength translates to increased passenger safety.
- Carbon nanotubes can also be effective semiconductors with the right arrangement of atoms.
- Scientists are still working on finding ways to make carbon nanotubes a realistic option for transistors in microprocessors and other electronics.

SOL GEL METHOD

- PRECURSOR-METAL ALKOXIDE
- HYDROLYSIS
- POLYCONDENSATION
- GEL NETWORK
- ACIDIC OR BASIC CATALYST

$$Si(OC_2H_5)_4 + 4H_2O \xrightarrow{\text{catalyst}} Si(OH)_4 + 4C_2H_5OH$$

$$Si(OH)_4 \longrightarrow SiO_2 + 2H_2O$$

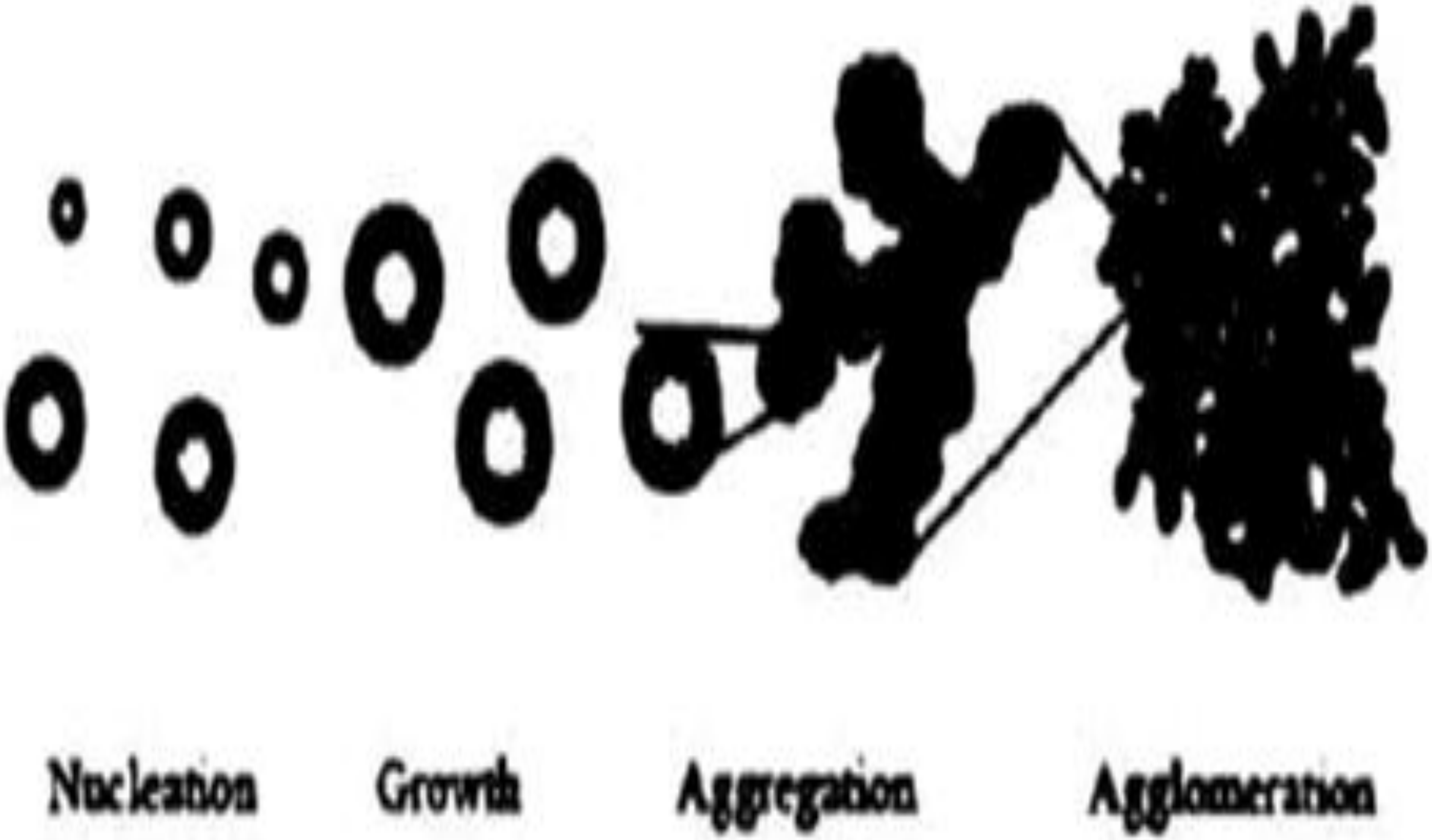


Figure 3.1: Growth of silica particles

USING TETRA ETHYL ORTHO SILICATE

- Exposing TEOS and WATER to ultrasound in the presence of acid catalyst
- The gelling time for this sonogel was about 115-200 minutes
- The gel is heated
- Fine powder of silica

PYROLYSIS

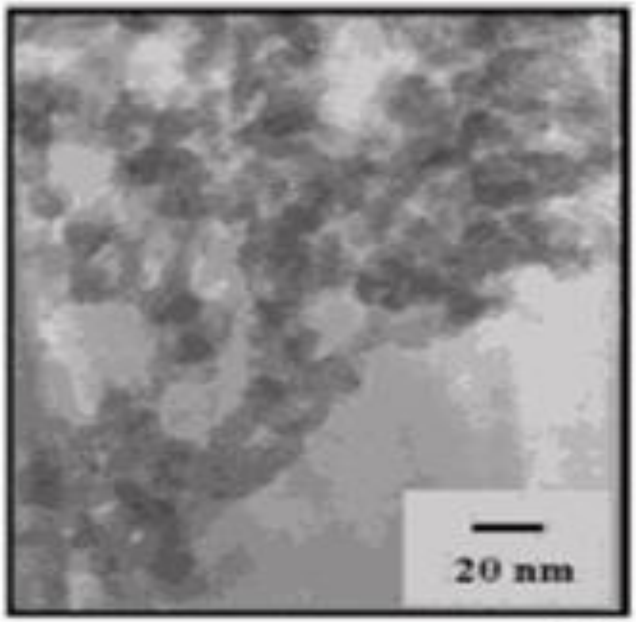
- PYROLYSIS OF TETRA ALKOXY SILANE
- PYROLYSIS OF TETRA CHLORO SILANE (BOTH IN PRESENCE OF WATER)

PRECIPITATION METHOD

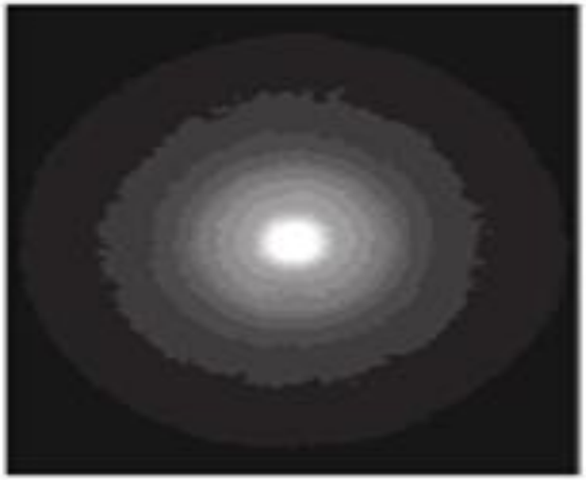
- PRECIPITATION OF SODIUM SILICATE SOLUTION WITH CONCENTRATED MINERAL ACIDS LIKE HCl,SULPHURIC ACID.

- $Na_2SiO_3 + 2HCl \rightarrow H_2SiO_3 + 2NaCl$
- $H_2SiO_3 \rightarrow SiO_2 + H_2O$

TEM IMAGE OF NANO SILICA



(b)



Precipitated Silica

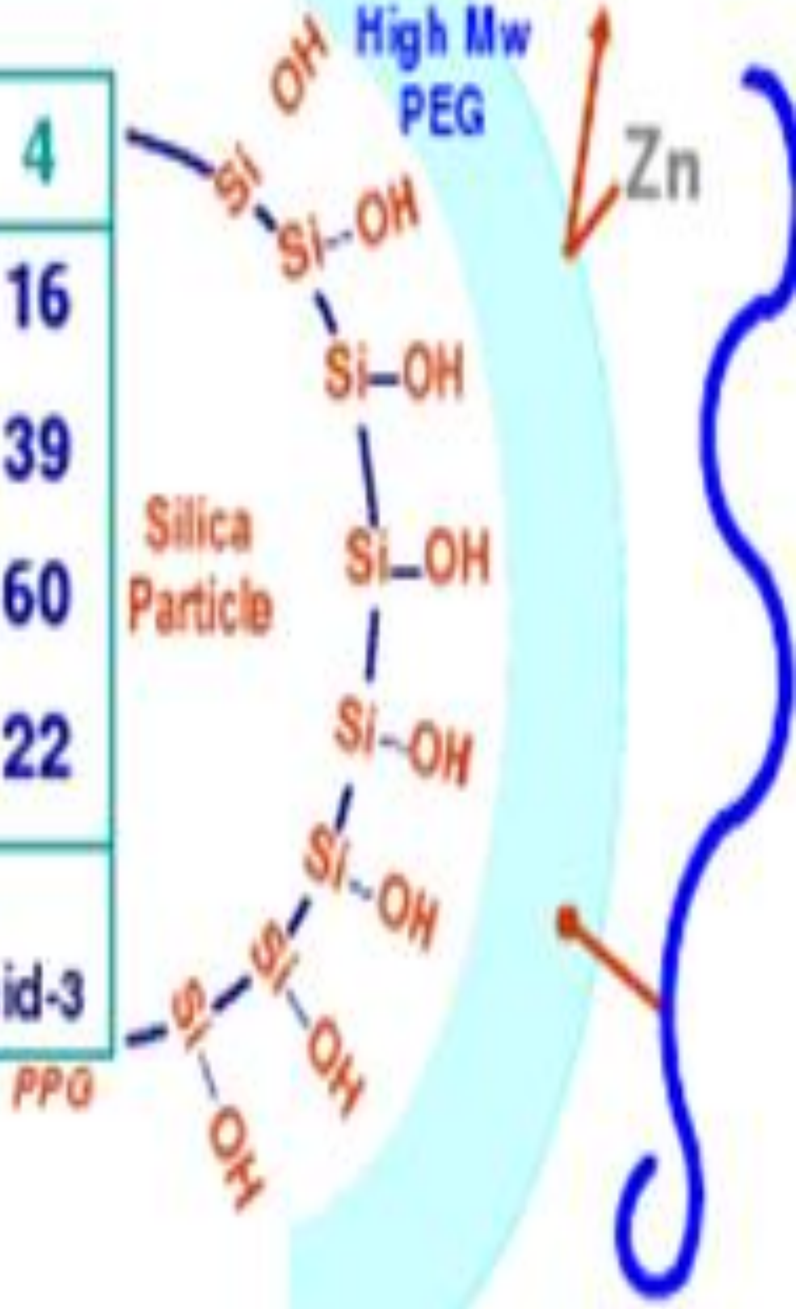
Water is a:

Barrier to soluble Zn, accelerators

Hindrance to rubber bonding

PEG 3350, phr	0	2	4
ODR, 144°C, T_{90} min	34	19	16
Viscosity, $ML_4$100	51	41	39
Hardness	59	66	60
Flexometer HBU, °C	32	29	22

NR-100; 150 m²/g silica-30; 35 m²/g silica-45; sulfur-2.8;MBS-1.5; DPG-0.3; ZnO-5; stearic acid-3

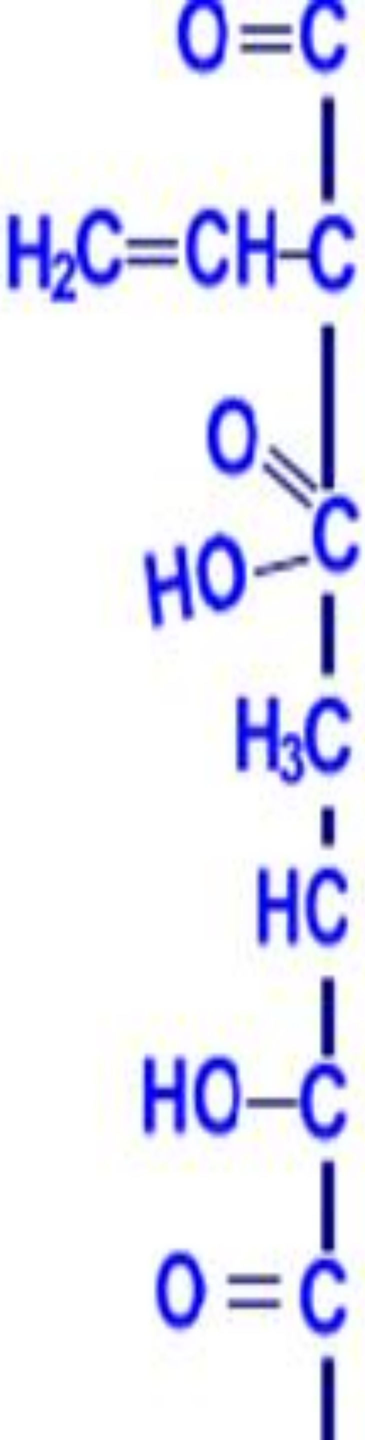


More is Better

Active sites on filler surface

Reactive surface treatments

Silanols on kaolin and silica surfaces can hydrogen bond, and they can react as acids.



Surface Treatments/Modifiers:

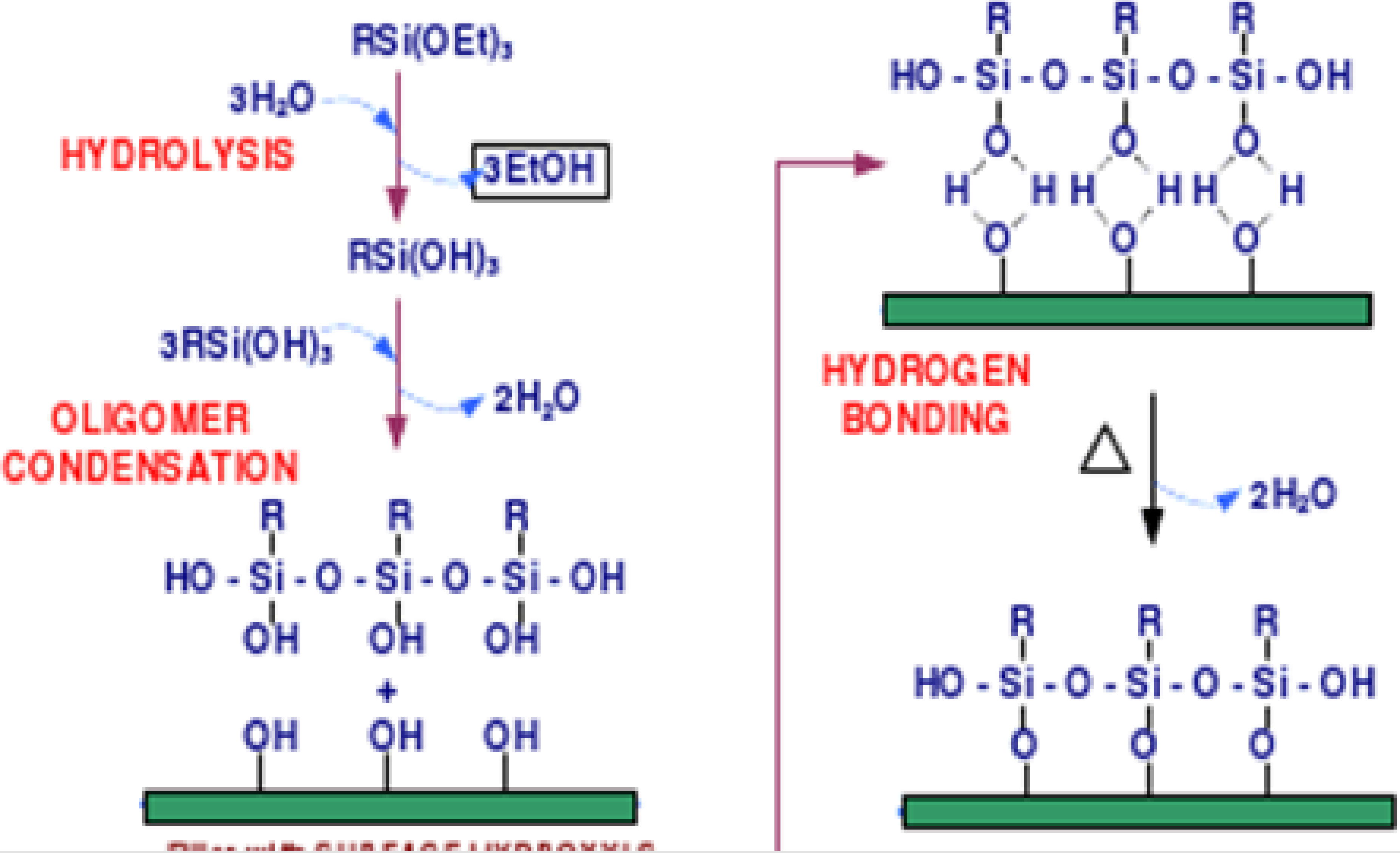
Silanes – $RSiX_3$

X is hydrolysable group (e.g., methoxy, ethoxy)

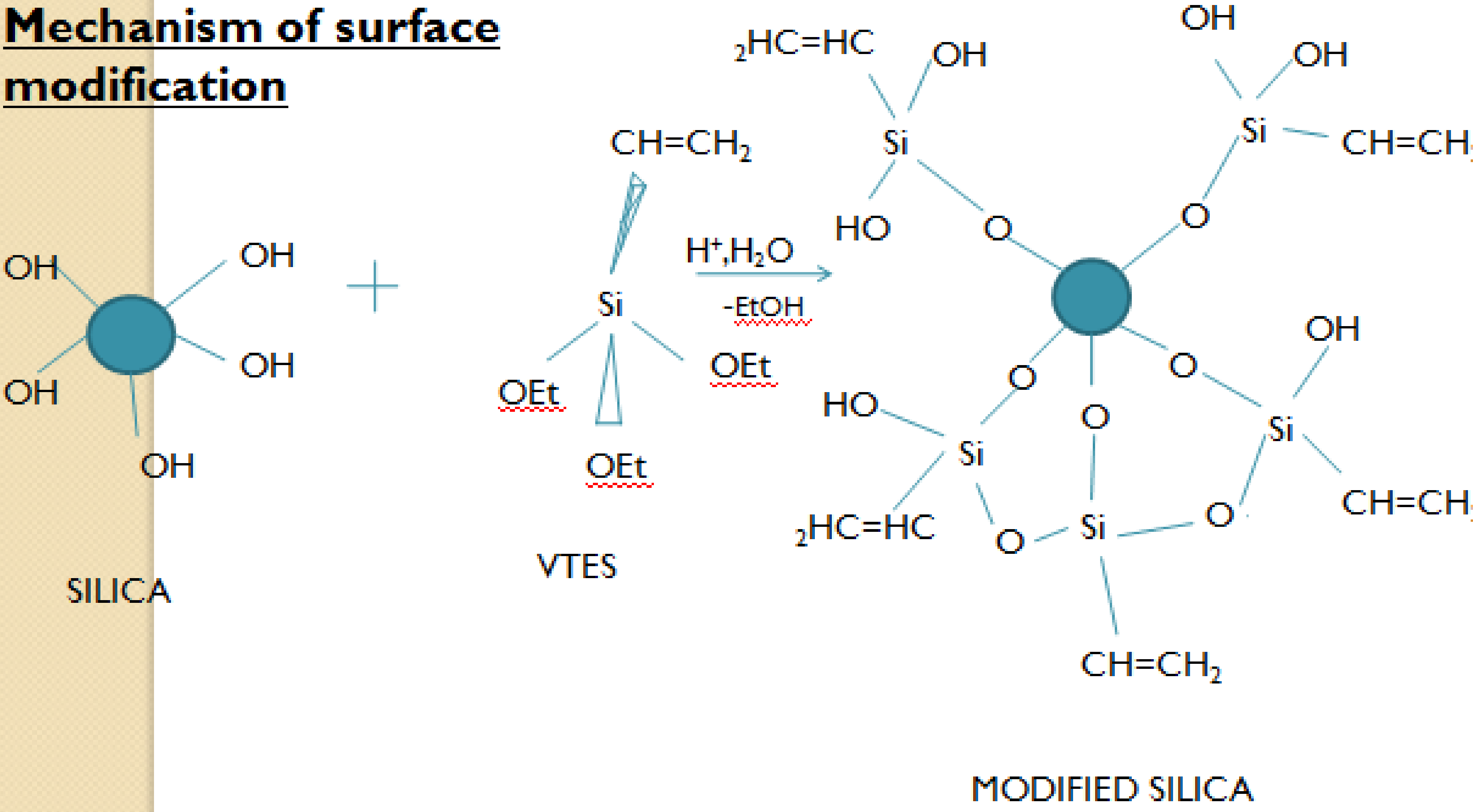
R is a organofunctional group (e.g., amino, mercapto, tetrasulfide, epoxy)

Particle-Matrix Compatibility

Silane-Mineral Reaction:

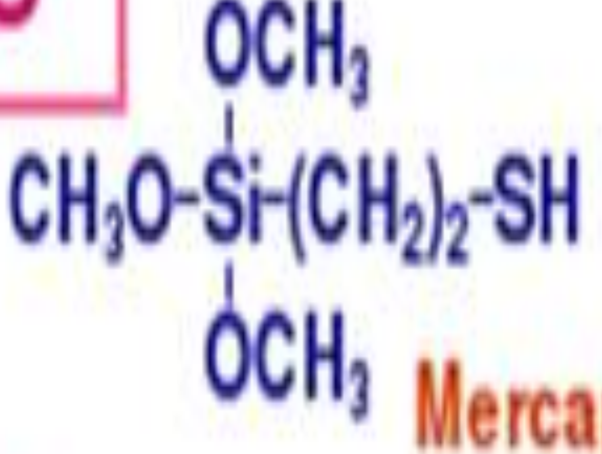


Mechanism of surface modification



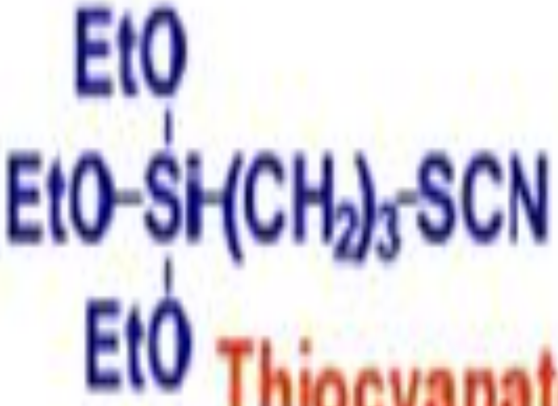
Egs: are vinyl silanes,epoxy silanes,amino silanes.

SILANES



$$\mathrm{CH_3O{-}\underset{\underset{OCH_3}{|}}{\overset{\overset{OCH_3}{|}}{Si}}{-}(CH_2)_2{-}SH}$$

Mercapto



$$\mathrm{EtO{-}\underset{\underset{EtO}{|}}{\overset{\overset{EtO}{|}}{Si}}{-}(CH_2)_3{-}SCN}$$

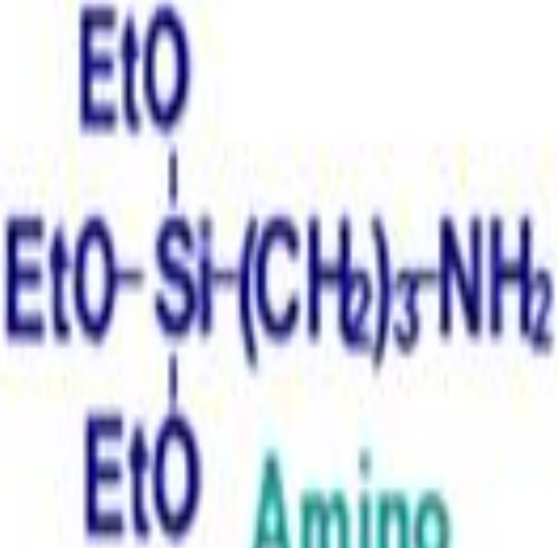
Thiocyanate

Sulfur
Cure

$$\mathrm{EtO{-}\underset{\underset{EtO}{|}}{\overset{\overset{EtO}{|}}{Si}}{-}(CH_2)_3{-}S_n{-}(CH_2)_3{-}\underset{\underset{OEt}{|}}{\overset{\overset{OEt}{|}}{Si}}{-}OEt}$$

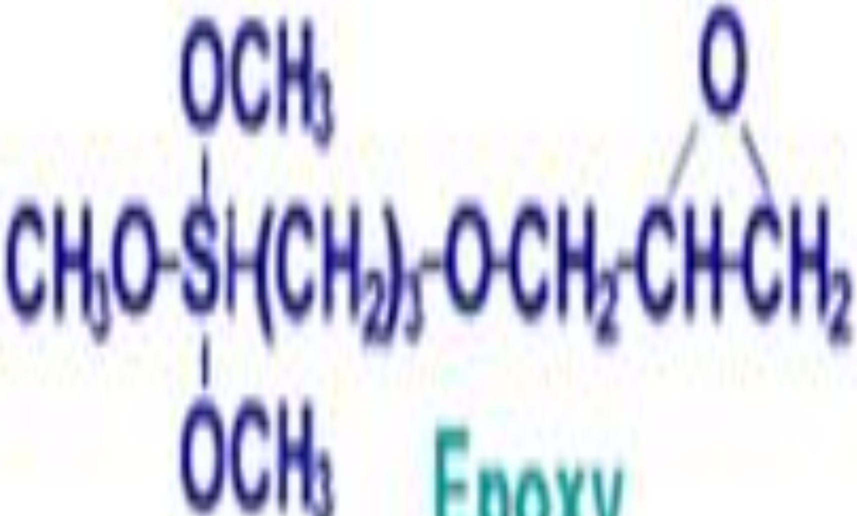
Polysulfide:
$n = 4$ or $n = 2$

Non-Sulfur Cure



$\mathrm{(EtO)_3Si{-}(CH_2)_3{-}NH_2}$

Amino

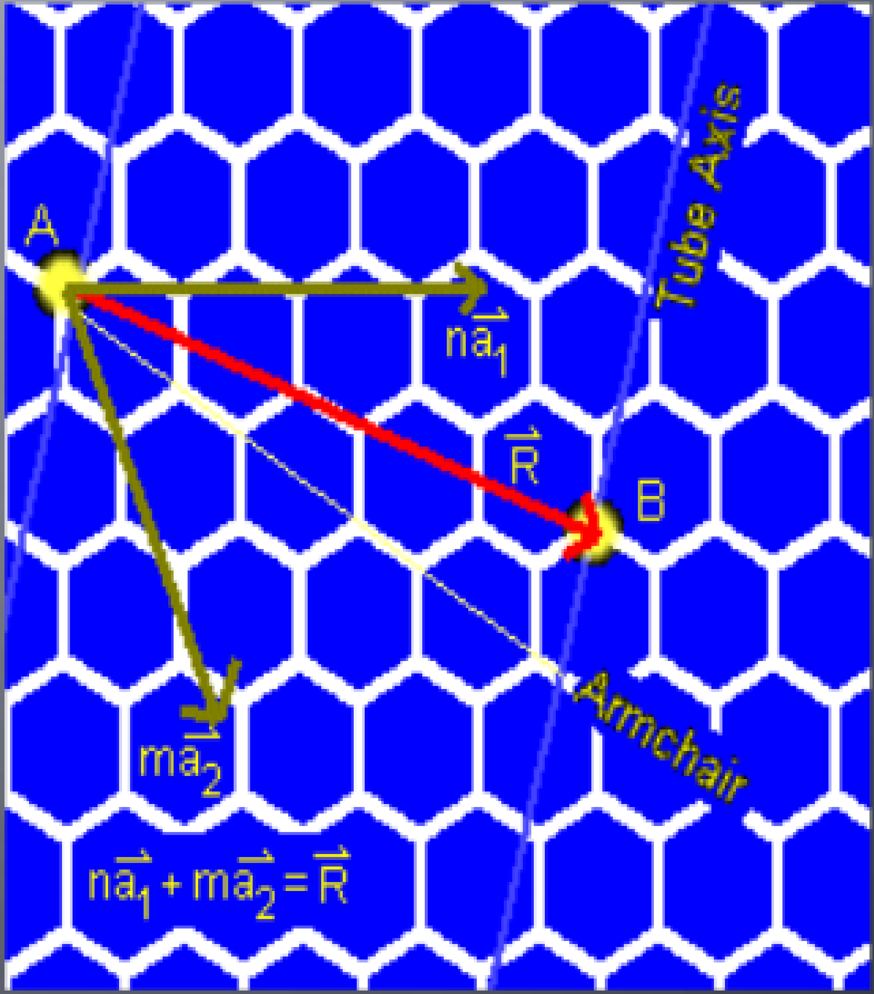


Epoxy

THANK YOU

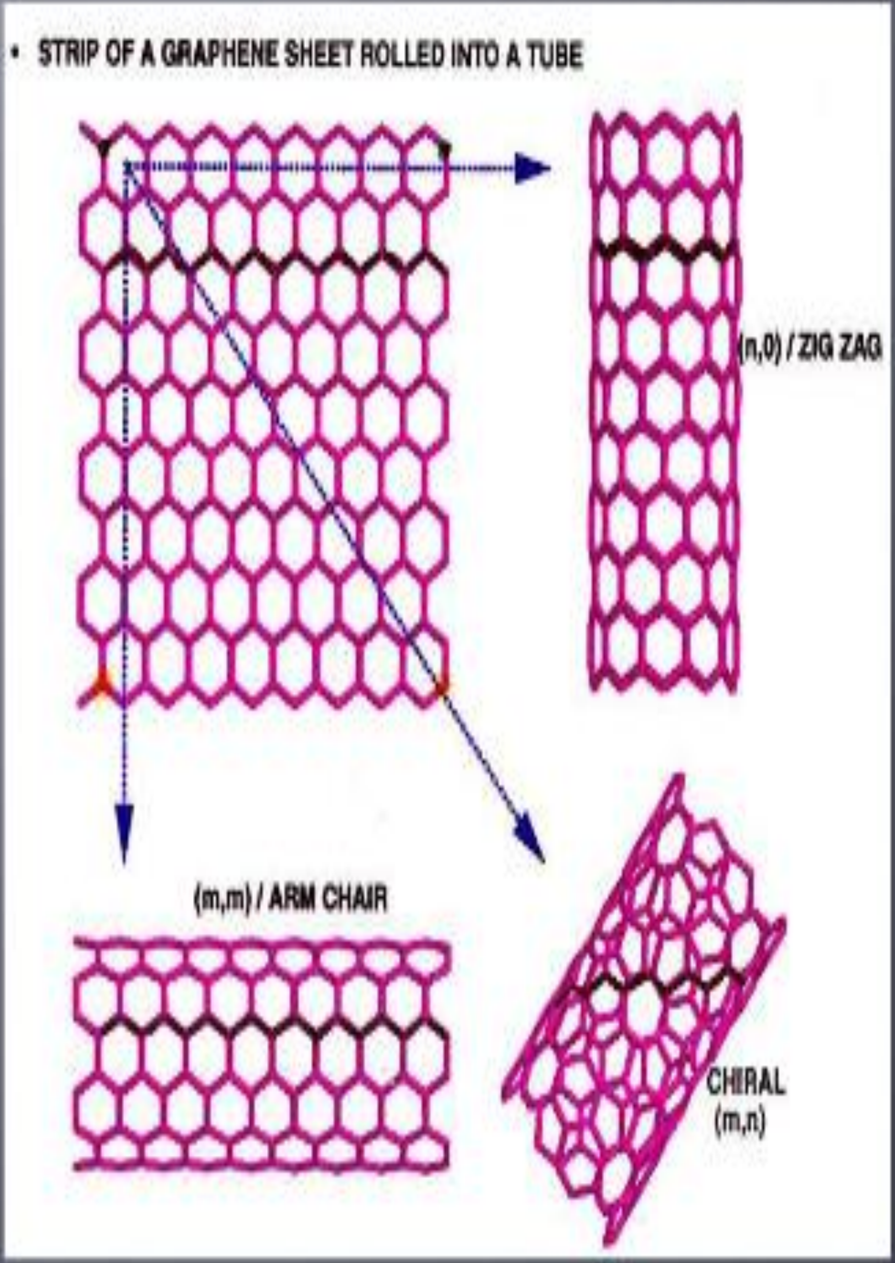
Nanotube Classification

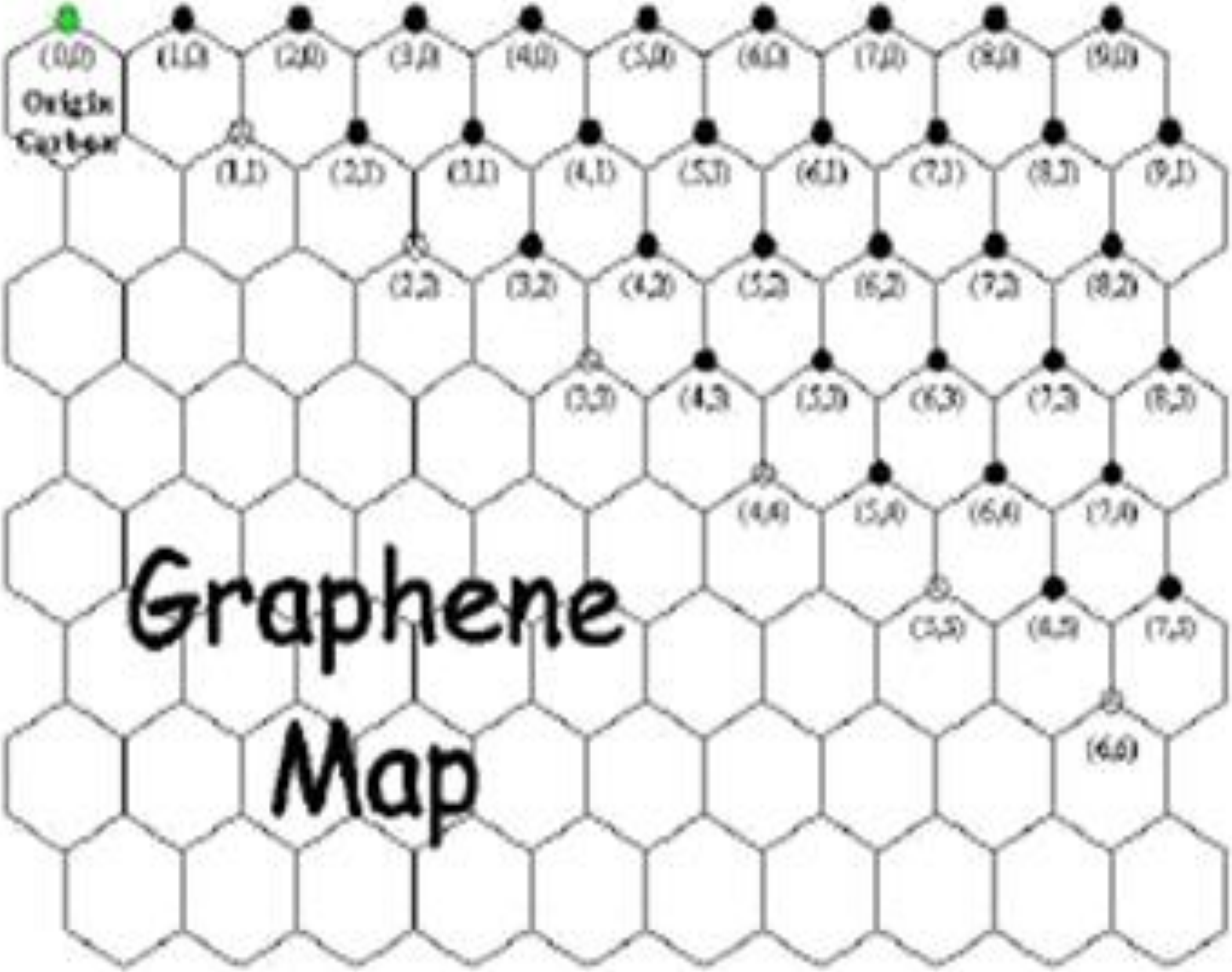
- Chirality - twist of the nanotube
- Described as the vector R (n, m)
- Armchair vector, R vector, angle Ø
- Ø = 0°, armchair nanotube
- 0° < Ø < 30°, chiral nanotube
- Ø > 30°, zigzag nanotube



- CNT exhibits extraordinary mechanical properties: Young's modulus over 1 Tera Pascal, as stiff as diamond, and tensile strength ~ 200 GPa.

- CNT can be metallic or semiconducting, depending on (m-n)/3 is an integer (metallic)
- or not (semiconductor).

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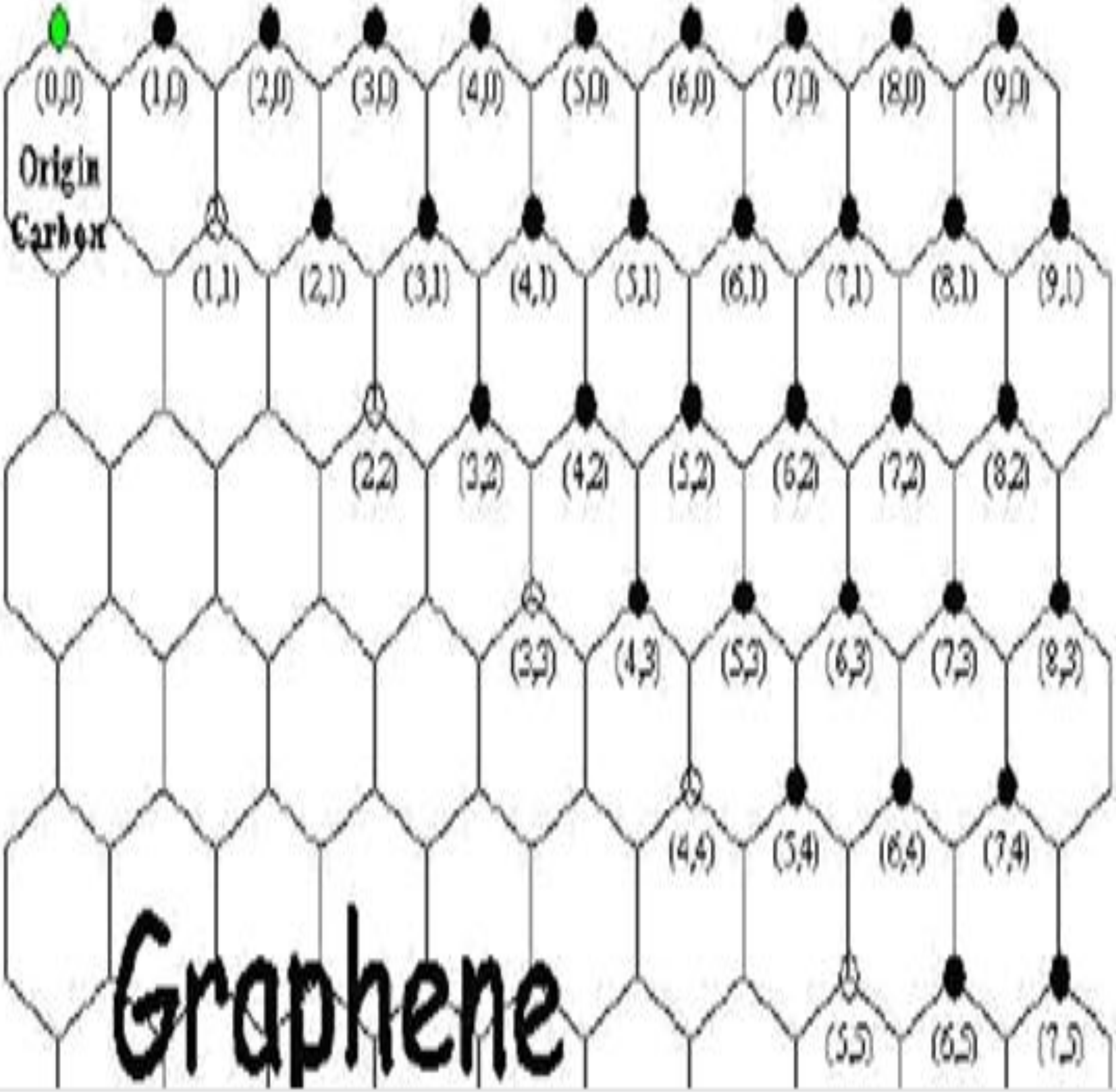
Graphene
Map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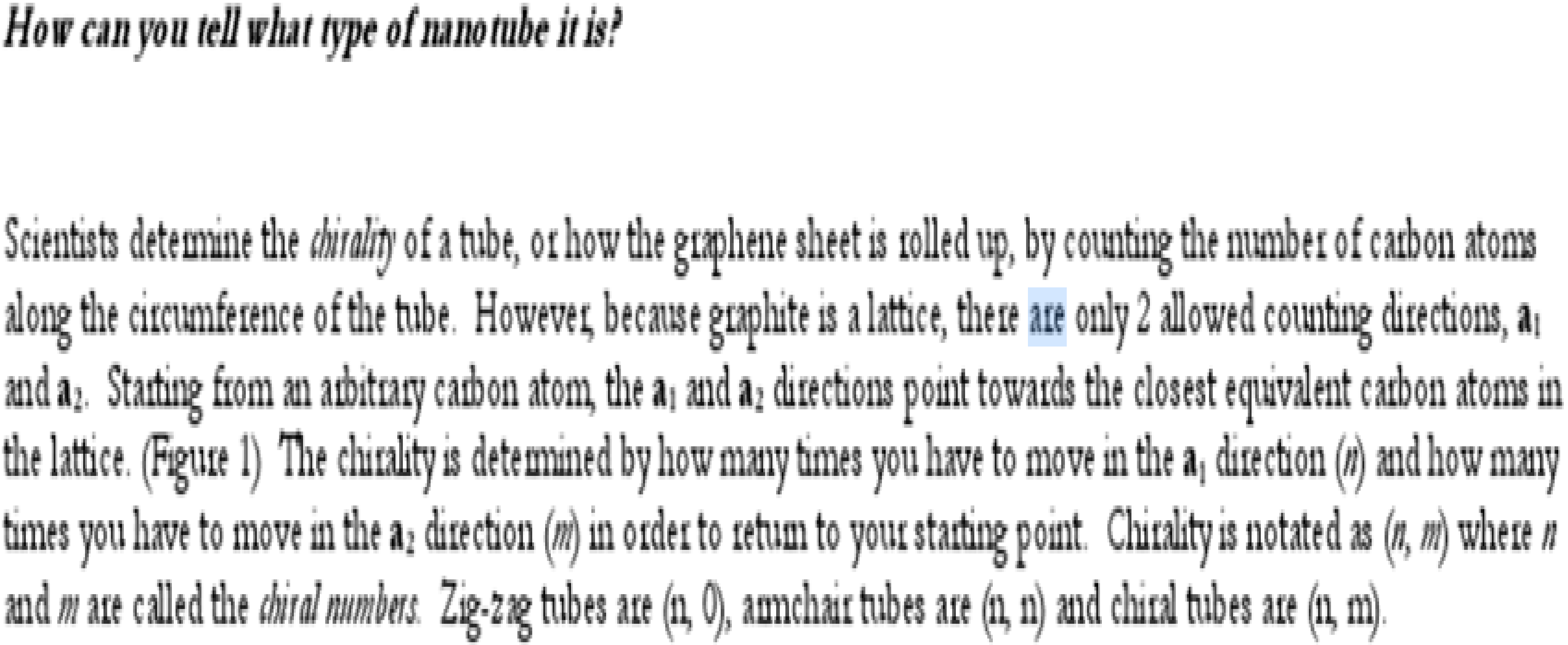
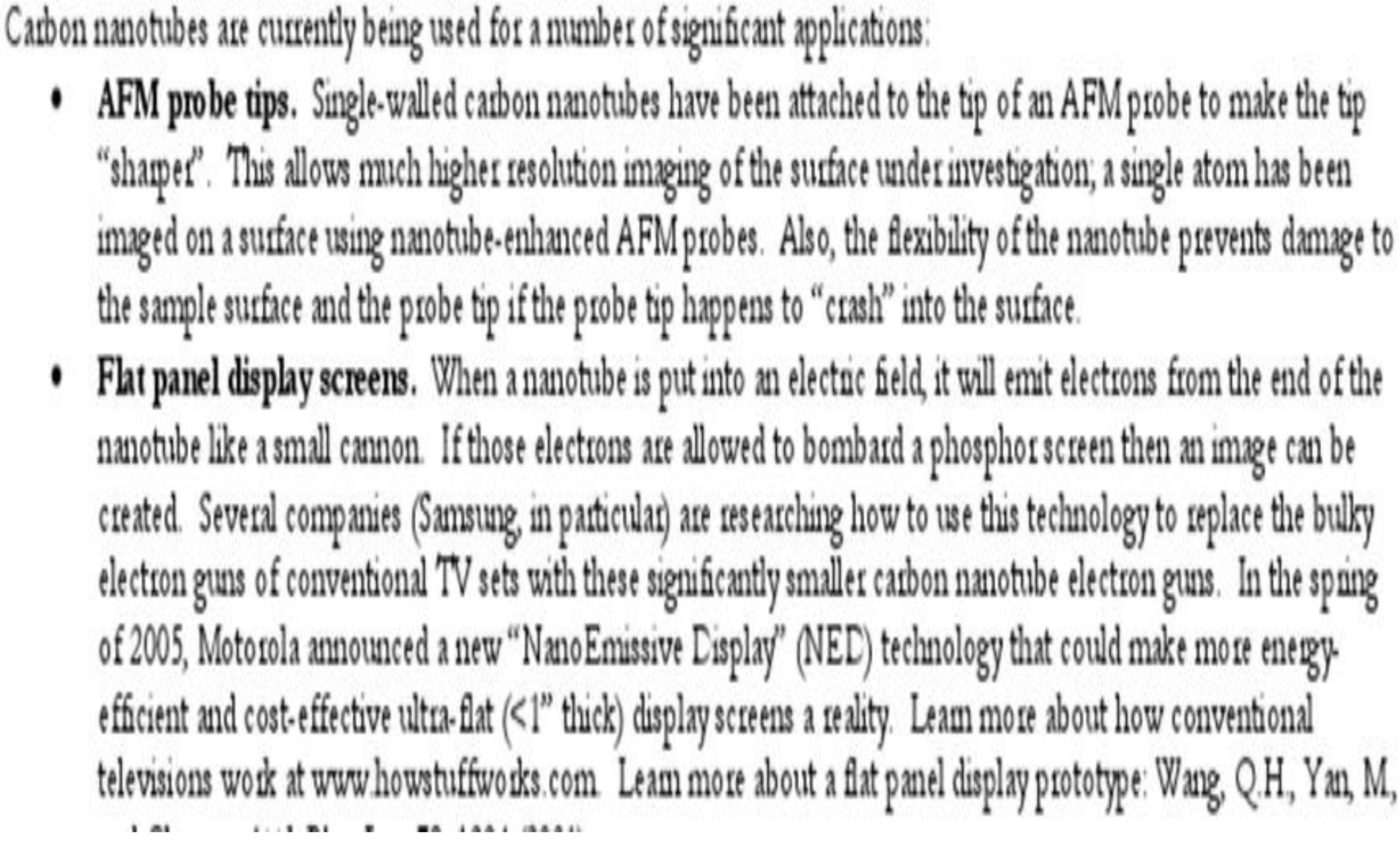
Graphene



How can you tell what type of nanotube it is?

Scientists determine the *chirality* of a tube, or how the graphene sheet is rolled up, by counting the number of carbon atoms along the circumference of the tube. However, because graphite is a lattice, there are only 2 allowed counting directions, $\mathbf{a}_1$ and $\mathbf{a}_2$. Starting from an arbitrary carbon atom, the $\mathbf{a}_1$ and $\mathbf{a}_2$ directions point towards the closest equivalent carbon atoms in the lattice. (Figure 1) The chirality is determined by how many times you have to move in the $\mathbf{a}_1$ direction (*n*) and how many times you have to move in the $\mathbf{a}_2$ direction (*m*) in order to return to your starting point. Chirality is notated as (*n*, *m*) where *n* and *m* are called the *chiral numbers*. Zig-zag tubes are (n, 0), armchair tubes are (n, n) and chiral tubes are (n, m).

To count an armchair or chiral tube, it is necessary to move along both the $\mathbf{a}_1$ and a_2 directions. If you were to count only along the $\mathbf{a}_1$ direction, you would never be able to return to your starting point; it is necessary to count along the $\mathbf{a}_1$ direction, then turn and count along the $\mathbf{a}_2$ direction in order to return to the starting point. For example, to count a (3, 3) armchair tube, choose an arbitrary carbon atom as your starting point (red star, Figure 3). Move to the closest carbon atom in the $\mathbf{a}_1$ direction. Move a total of 3 times in the $\mathbf{a}_1$ direction. You will notice that if you continue in the $\mathbf{a}_1$ direction, you will not return to your starting point. From the same carbon atom you just reached, turn and move 3 times in the $\mathbf{a}_2$ direction. You should have returned to your starting point. Chiral and armchair nanotubes can both be counted in this manner.

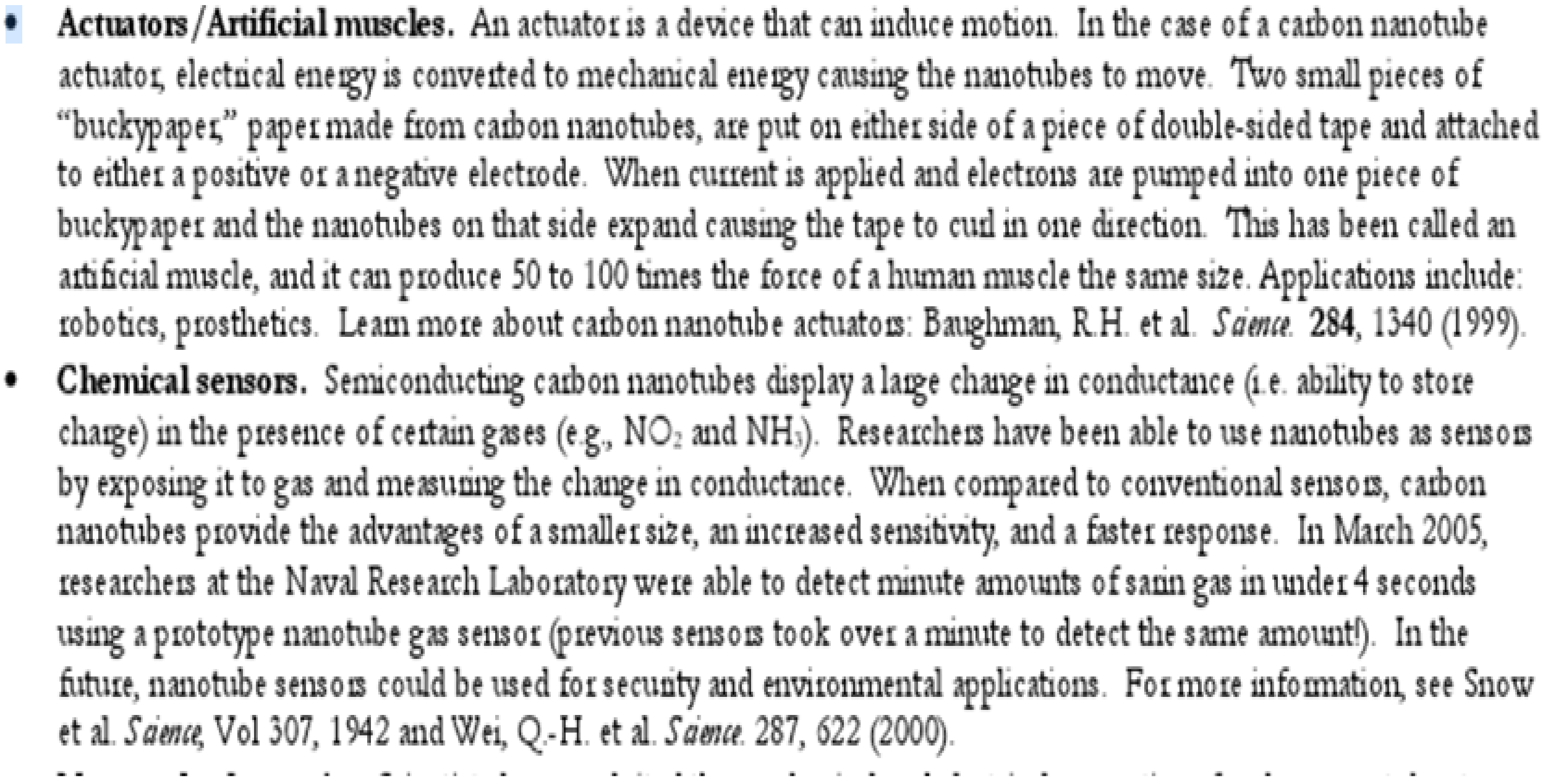


Carbon nanotubes are currently being used for a number of significant applications:

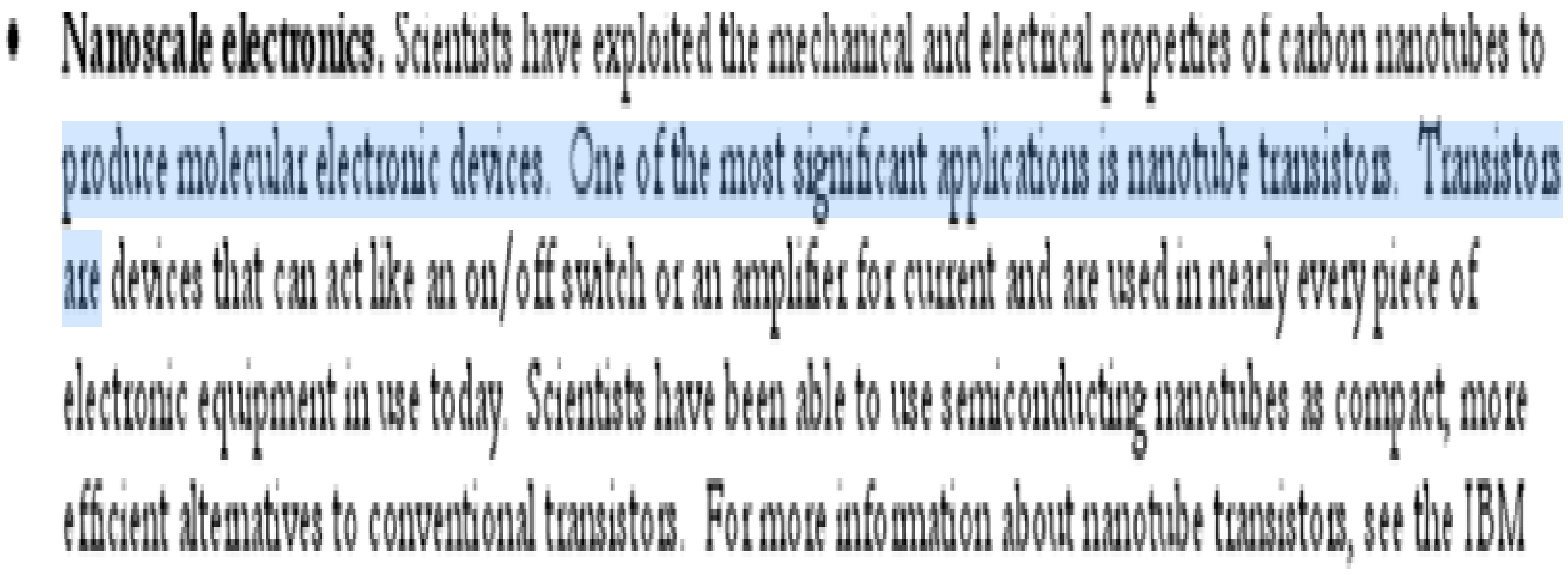
- **AFM probe tips.** Single-walled carbon nanotubes have been attached to the tip of an AFM probe to make the tip "sharper". This allows much higher resolution imaging of the surface under investigation; a single atom has been imaged on a surface using nanotube-enhanced AFM probes. Also, the flexibility of the nanotube prevents damage to the sample surface and the probe tip if the probe tip happens to "crash" into the surface.
- **Flat panel display screens.** When a nanotube is put into an electric field, it will emit electrons from the end of the nanotube like a small cannon. If those electrons are allowed to bombard a phosphor screen then an image can be created. Several companies (Samsung, in particular) are researching how to use this technology to replace the bulky electron guns of conventional TV sets with these significantly smaller carbon nanotube electron guns. In the spring of 2005, Motorola announced a new "NanoEmissive Display" (NED) technology that could make more energy-efficient and cost-effective ultra-flat (<1" thick) display screens a reality. Learn more about how conventional televisions work at www.howstuffworks.com. Learn more about a flat panel display prototype: Wang, Q.H., Yan, M.,

- **Nanocomposite materials.** Dr. Morinobu Endo at Shinshu University mixed nylon with carbon *fibers* (100-200 nm diameter threads made in a similar manner to nanotubes) creating a nanocomposite material that could be injected into the world's smallest gear mold (as of 2004). The carbon fibers have excellent thermal conductivity properties that cause the nanocomposite material to cool more slowly and evenly allowing for better molding characteristics of the nanocomposite. The "improved" properties of the nanocomposite allow it more time to fill the tiny micron-sized mold than nylon would by itself. The tiny gears currently are being made in collaboration with Seiko and Showa Denko KK (SDK) for use in watches. (see www.sdk.co.jp/contents_e/news/news02/02-02-06.htm)

- **Hydrogen storage.** As we move into a new century, there is a global focus on a cleaner environment and developing renewable energy sources. To that end, a great deal of research is being devoted to hydrogen fuel cells. When oxygen and hydrogen react in a fuel cell, electricity is produced and water is formed as a byproduct. If industry wants to make a hydrogen-oxygen fuel cell, scientists and engineers must find a safe way to store hydrogen gas needed for the fuel cell. Carbon nanotubes may be a viable option. Carbon nanotubes are able to store hydrogen and could provide the safe, efficient, and cost-effective means to achieve this goal. Hydrogen atoms bond to the carbon atoms of the nanotube, and can be later released with slight changes in temperature and pressure. While nanotube-based hydrogen fuel cells are promising, there are no viable products on the market yet. (for information on how nanotubes store hydrogen, see Dillon, A.C. et al. *Science.* **286**, 1127 (1999).)



- **Actuators/Artificial muscles.** An actuator is a device that can induce motion. In the case of a carbon nanotube actuator, electrical energy is converted to mechanical energy causing the nanotubes to move. Two small pieces of "buckypaper," paper made from carbon nanotubes, are put on either side of a piece of double-sided tape and attached to either a positive or a negative electrode. When current is applied and electrons are pumped into one piece of buckypaper and the nanotubes on that side expand causing the tape to curl in one direction. This has been called an artificial muscle, and it can produce 50 to 100 times the force of a human muscle the same size. Applications include: robotics, prosthetics. Learn more about carbon nanotube actuators: Baughman, R.H. et al. *Science.* **284**, 1340 (1999).
- **Chemical sensors.** Semiconducting carbon nanotubes display a large change in conductance (i.e. ability to store charge) in the presence of certain gases (e.g., NO_2 and NH_3). Researchers have been able to use nanotubes as sensors by exposing it to gas and measuring the change in conductance. When compared to conventional sensors, carbon nanotubes provide the advantages of a smaller size, an increased sensitivity, and a faster response. In March 2005, researchers at the Naval Research Laboratory were able to detect minute amounts of sarin gas in under 4 seconds using a prototype nanotube gas sensor (previous sensors took over a minute to detect the same amount!). In the future, nanotube sensors could be used for security and environmental applications. For more information, see Snow et al. *Science*, Vol 307, 1942 and Wei, Q.-H. et al. *Science.* 287, 622 (2000).



- **Nanoscale electronics.** Scientists have exploited the mechanical and electrical properties of carbon nanotubes to produce molecular electronic devices. One of the most significant applications is nanotube transistors. Transistors are devices that can act like an on/off switch or an amplifier for current and are used in nearly every piece of electronic equipment in use today. Scientists have been able to use semiconducting nanotubes as compact, more efficient alternatives to conventional transistors. For more information about nanotube transistors, see the IBM

Explanation for structure

- The analogy of a rolled sheet of graphite is however used to define the many important electrical and mechanical properties that carbon nanotubes exhibit. Using a De Heer abacus the various configurations of carbon nanotubes can be defined by their "roll up" vector. The rolling angle lies between 0 and 30 degrees with the two extremes referred to as "zigzag" and "armchair" respectively. Any nanotube with a roll angle in-between is referred to as "chiral".
- This vector can be defined as a linear combination of base vectors *a* and *b* of the hexagon, i.e.

$r = n\,a + m\,b$