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A classroom activity on carbonaceous materials: Construction of graphite and diamond and experiments with electrical and adsorption properties

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ABSTRACT

A hands-on activity is presented for elementary school students to discover the composition of matter and its consequences on chemical and physical properties. Natural forms of carbon (coal, graphite and diamond), synthesized forms (charcoal and activated carbon), and the differences in their physical properties are listed and discussed. Students built a flat hexagonal portion of the graphene sheets of graphite and a tetrahedral portion of the 3D structure of diamond. They experimented with conductivity of a graphite pencil and compared it with that of a wood stick and a copper wire. They also explored adsorption properties of activated carbon by decolorizing a grenadine solution.



KEYWORDS

Elementary / Middle School Science, Hands-On Learning / Manipulatives, Demonstrations, Conductivity, Descriptive Chemistry, Dyes /Pigments, Separation Science, Solid State Chemistry, Surface Science.

INTRODUCTION

In most countries of the world, effort has increased to enhance scientific education, in order for future citizens to better understand their surrounding world and be able to analyze political decisions *e.g.* in terms of health or environment. Efforts are often conducted jointly between educators and scientists^{1,2} and many outstanding approaches have been employed^{3,4} to fight against “chemophobia”⁵ and transfer chemistry knowledge in informal settings^{6,7}. The hands-on activity on carbonaceous materials presented in this article was initially set up for “Chimie & Terroir”⁸, an out-of-class scientific outreach event, organized by “Chimie et Société”⁹, a division of the Fondation de la Maison de la Chimie¹⁰. It was conducted twice with 300 students each time over three days and was part of the action “Caravane de la chimie”¹¹. Following a demand from teachers, the activity was proposed in class, in line with the program¹² of Cycle 3 of French elementary schools (ages 9-11). The following acquisition of skills in science and technology is recommended: *“Acquire the scientific language necessary to analyze and describe the observations and experiments allowing understanding the world around us, using texts and diagrams; conduct experiments to acquire spatial and temporal benchmarks and notions of scale; describe the state and constitution of matter on a macroscopic scale; identify the main families of materials and their classification according to their physical and chemical properties”*. We report here on how the activity was transferred to a class so as to provide teachers with materials and instructions for reproducing it.

THE ACTIVITY

The activity was conducted in a class of fifteen children, aged 10, in two sessions of one hour each. The teacher used the activity during further science class (one hour weekly for four weeks). It is recommended that this activity is conducted after introducing atom composition through the activity reported by L. Cipolla and L. A. Ferrari¹³.

During the first part of the first session (first 30min), discussion was conducted with the students to:

- list carbonaceous materials accessible in everyday life and separate natural from synthesized materials;
- explain that carbon occurs naturally on earth as coal, graphite and diamond;
- identify the location of coal and diamond on earth;

- explain the formation of coal and diamond, and that of charcoal and activated carbon;
- list the physical properties of coal, charcoal, activated carbon and diamond and identify the differences.

During the second part of the first session (second 30min), each student successively:

- built the flat hexagonal arrangement of carbon in graphite to observe the planar organization;
- built the tetrahedral arrangement of carbon in diamond and associate the tetrahedrons to figure out the three-dimensional organization.

During the second session (1hr), students ran experiments to:

- compare the electrical conductivity of a wood chopstick, a graphite pencil and a copper wire;
- explore the adsorption properties of activated carbon by decolorizing a grenadine solution.

The students filled a worksheet after each period (Supporting Information 1 “student worksheet”, p. 5-8). In a final discussion, students were asked to list the properties they had collected from the experiments.

Carbonaceous materials: natural and synthesized

When asking the students what kind of carbonaceous materials they knew and for what use, they cited charcoal and coal. This was an opportunity to make the difference between natural and synthesized carbonaceous materials by listing them on a whiteboard (Table 1), and to add new entries. We showed samples of lignite, anthracite (Figure 1), charcoal, activated carbon and a fabric made of woven carbon fibers.

Natural forms of carbon and applications	Synthesized forms of carbon and applications
<p>Coal: heating</p> <p>Lignite: heating</p> <p>Anthracite: heating</p> <p>Graphite: pencil</p> <p>Diamond: jewelry, abrasives</p>	<p>Charcoal: barbecue</p> <p>Activated carbon: aquarium, water and air purification, medicine</p> <p>Carbon fibers: carbon composites (tennis racket, bicycle frame)</p> <p>Synthetic diamond : abrasives</p>

Table 1. Classification of current natural and synthetic carbonaceous materials. The words in green correspond to most frequent answers by students. The table is not exhaustive of all applications of carbonaceous materials but limited to few known uses in everyday life.

Charcoal is actually made of 70-90% of carbon, but is man-made by the pyrolysis of wood, called carbonization. However, the carbonization process is a rapid process (2-4 days) compared to the natural formation of coal, a fossil fuel resulting from the decomposition of plants¹⁴⁻¹⁶. Diamond is another natural form of carbon but can also be synthesized (*e.g.* by chemical vapor deposition from methane¹⁷, or at high pressure and temperature from graphite¹⁸). Activated carbon and carbon fibers are other examples of synthesized forms of carbon. Activated carbon is produced in two stages: (1) the carbonization of various starting materials (wood, peat, lignite, bones, coconut shell, bio wastes, etc) and (2) a treatment that removes the 10-30% remaining organic residues from charcoal and generates porosity^{19,20}. Activated carbon offers a large adsorbent surface area that can be used, *e.g.* for drinking water filtration, air purification, supported catalysis. Carbon fibers are used in composite materials and are prepared from synthetic polymers following three stages: (1) oxidative stabilization of the polymers, (2) carbonization and (3) graphitization²¹.

The natural forms of carbon: formation of coal and diamond

A short video (*e.g.*²²) explaining the formation of coal was used at the beginning of the activity to focus attention and help to understand²³ the transformation of vegetation into coal. Nowadays extracted coal results from vegetation that was transformed typically over 300 to 500 million years: the first plants appeared at the Devonian period (360-420 million years ago, MYA), the Carboniferous period (300-360 MYA) and the Permian period (250-300 MYA) provided 13% and 30% of coal resources, respectively; 12% of resources come from Jurassic (145-200 MYA) and 15% from lower Cretaceous (100-145 MYA) periods; Paleogene period (23-66 MYA) mainly resulted in lignite.^{24,25} Sedimentation and movements of the earth crust buried the altered vegetation that was exposed to high temperatures and pressures and progressively transformed it into peat, lignite, coal, anthracite and graphite. This transformation is called coalification and the degree of coalification is measured by the carbon content: from 50 % in wood, 50-55 % in peat to more than 90% in anthracite and 100% in graphite (Figure 1).

Coal formation



Sedimentation
of plants



Peat



Lignite



Anthracite



Coalification duration and carbon content

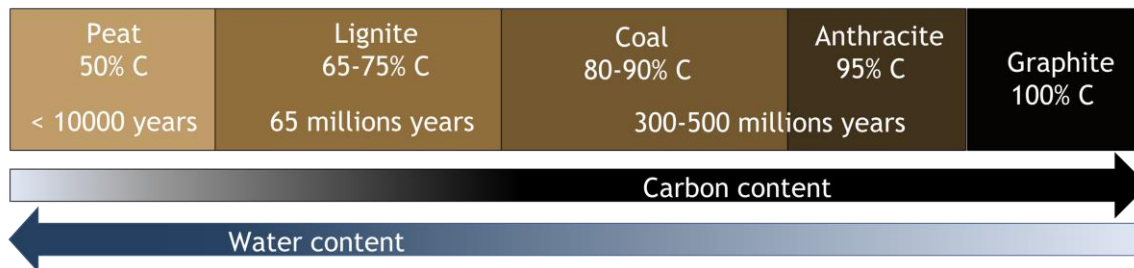


Figure 1. The steps and duration of the coalification process: from plants to graphite.

Diamond is another natural form of carbon containing 100% of carbon, however, the formation of diamond requires more extreme conditions of temperature and pressure compared to coal. Moreover, diamond is formed at deeper conditions than coal, at a minimum of 150 km from the earth's surface *versus* a maximum of 3 km for coal, corresponding to the portion of the earth crust dating back more than 1.5 billion years²⁶. Consequently, diamond formation occurred far before plants occupied earth. These long periods of time were not easy for students to grasp at their age. A geological time scale starting at the earth's formation was used to illustrate the timing of diamond formation, the presence of the first plants, the Carboniferous period, the period of dinosaurs, and the first humans in comparison to the duration of human being lifetimes (Figure 2).

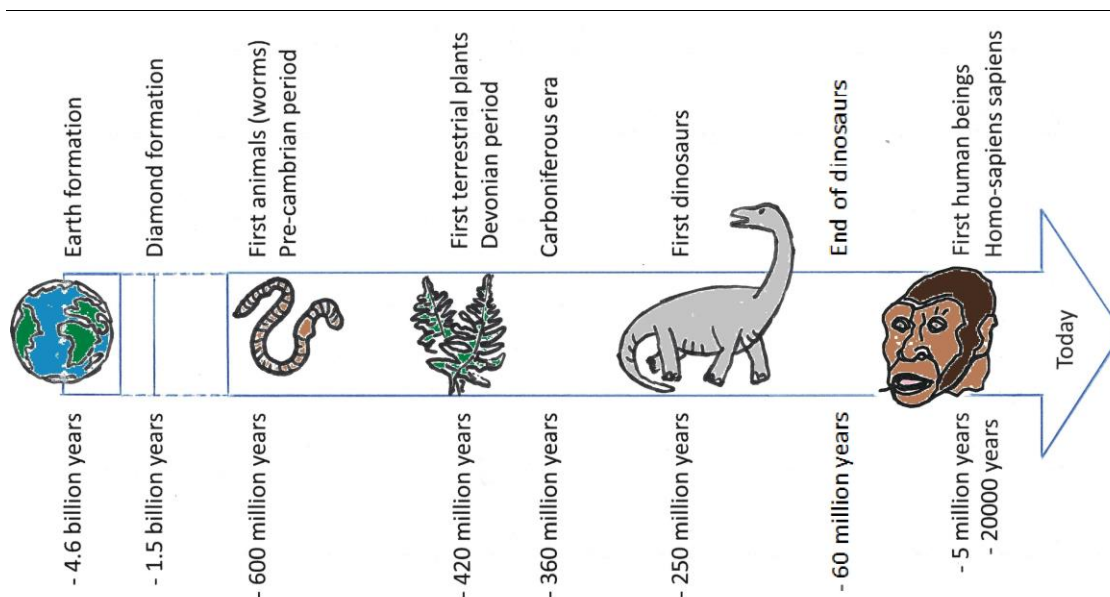


Figure 2. This geological time scale can be set up on a 5m ribbon to figure out duration by transposing time to distances. Men appear at 5 mm, dinosaurs at 25 cm, coal formation at 36 cm, first plants at 42 cm, first animals as worms at 60 cm, diamond at 1.5m, and earth at 4.6 m. Each millimeter represents 1 million years.

Graphite and diamond are both made of carbon

Children have all used graphite pencils and seen diamonds on rings. They were asked to list the differences between graphite and diamond in terms of color and hardness: graphite is black and soft, while diamond is transparent and hard. We explained that, although they look very different, both graphite and diamond are made of 100% carbon. If we used a microscope that magnifies 10 billion times, we could see how carbon atoms are organized in graphite and diamond. This would help understanding their properties. Note that the activity described by L. Cipolla and L. A. Ferrari¹³ on atom composition had been conducted prior to that on carbonaceous materials, including the association of atoms into molecules with the example of water and methane molecules. We could therefore explain that each carbon atom has four electrons to share with neighbors. When two atoms engage one electron each, a bond is formed. In diamond, carbon atoms engage all their four electrons to bond to four other carbon atoms arranged at the apex of triangular shaped pyramids named tetrahedrons. In graphite, carbon atoms bond to three other carbon atoms and form flat hexagons²⁷. As reported by Siodlak²⁸ and Kao²⁹, three-dimensional visualization of the organization of atoms in matter is useful for understanding their properties. The students built hexagons using toothpicks and polystyrene balls³⁰ (see templates in Supporting Information 2, p. 2). Bottle caps could also be used²⁸. They were able to figure out that the hexagons are planar. They connected their own hexagon to others to form the hexagonal pavement emulating the structure of one layer in

graphite, named graphene. They then built the tetrahedral arrangement of carbon in diamond (see template in Supporting Information 2, p. 3) and connected them together. They could compare the planar (two-dimensional) arrangement in graphite to the three-dimensional arrangement in diamond (Figure 3).

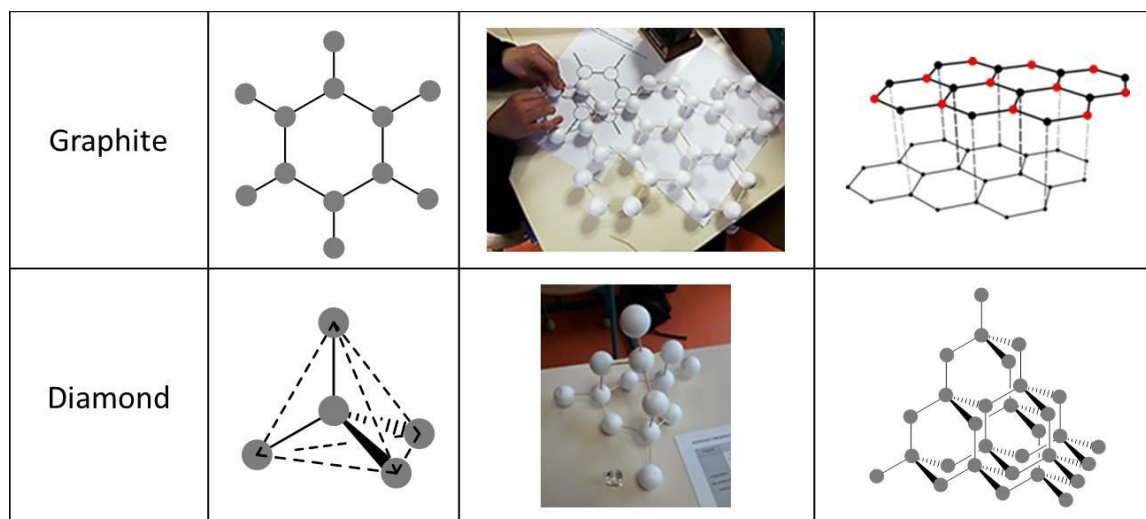


Figure 3. The organization of carbon atoms in graphite and diamond; construction of the hexagonal and tetrahedral units and assemblies of the units in two-dimension for graphite and in three dimensions for diamond.

Properties of graphite and diamond: hardness, color and conductivity

In graphite, the carbon richer form of coal, the hexagonal sheets are stacked, and gas is present between layers³¹; this organization makes the layers able to slip over each other, which explains that graphite is a soft material. Graphite is used in pencils and layers of graphene are deposited on paper during writing. In diamond, carbon atoms are strongly bonded in all directions thereby forming a structure which cannot be easily deformed: diamond is a hard material.

In graphite, each carbon atom has one delocalized electron (contributing to delocalized π -bonds). These delocalized electrons form a cloud over and below each layer; this electronic cloud absorbs light and can support electrical transport. In diamond, carbon atoms use all their four electrons (in σ bonds) to bond to four other carbon atoms; there are no delocalized electrons to block light transmission or support electrical transport. Therefore, graphite is black and conductive while diamond is transparent and insulating.

For reasons of availability, experiments focused on graphite-containing materials: the graphite stick of a pencil was used for the conductivity experiment and the adsorption properties were explored using activated carbon for aquarium use.

Conductivity of graphite: light a bulb

A flash light equipped with clips (Figure 4), was given to the students. They successively connected the clips to a wood chopstick, a graphite pencil (carpenter pencil) and a copper wire and observed the brightness of the bulb; they concluded that wood is an insulator, and the graphite pencil conducts less than the copper wire. We explained that:

- Wood, which transforms into graphite after coalification, is made of cellulose and lignin, *i.e.* organic matter containing carbon, hydrogen and oxygen atoms organized in such a way that no electrons are available to transport electricity. Wood is insulating;
- The graphite pencil contains conducting graphite, in which delocalized electrons support the transport of electricity, and clay which is insulating;
- Copper is a metal which conducts electricity as graphite but better than the mixture of graphite and clay, explaining that the bulb is brighter.

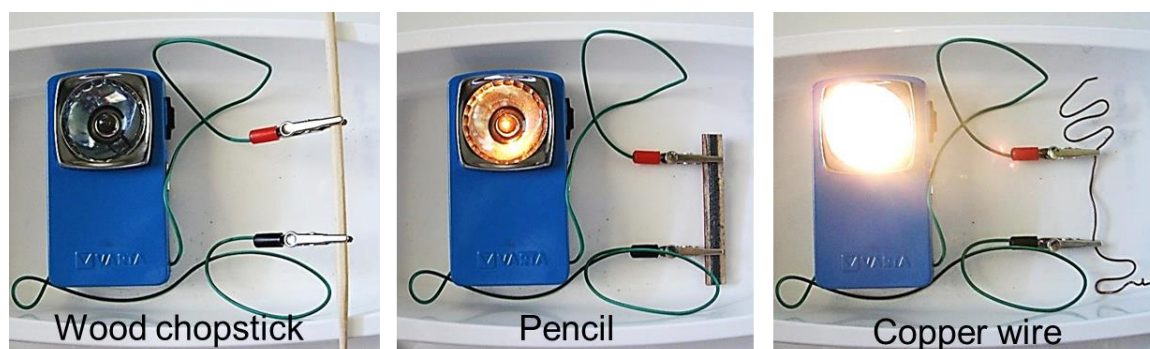


Figure 4. A flash light with switch externalized: the switch is replaced by clips. The students connect the clips to a chopstick, a graphite pencil and a copper wire and observe the brightness of the bulb.

Adsorption properties of activated carbon, a synthesized form of carbon: decolorizing grenadine

The students received a column (see alternative equipment in Supporting Information 2, p.7) and filled it with activated carbon and water (Figure 5). Help was given by the teacher to avoid air entrapment while packing the column. They added 200mL of a solution of grenadine

(or food coloring) to the column and collected the filtrate at 1 drop per second. They observed that the liquid filtered is colorless. We explained that the color is due to a dye contained in the grenadine syrup. When water and grenadine are passed through activated carbon, the dye is trapped in the pores of the surface of activated carbon: we used an egg box and ping-pong balls to illustrate the adsorption process (See Supporting Information 2, p. 7). The dye is separated from water and grenadine, it accumulates on the surface of the activated carbon and can be removed from it. Teachers can find additional information on the adsorption of a dye on activated carbon in the laboratory experiment for undergraduate students published in this journal by A. Martins and N. Nunes³².



Figure 5. from left to right: preparation of the column, water and grenadine solution, colorless filtrate.

MATERIALS AND HAZARDS

Grain-like “JBL Carbonec-activ” activated carbon was purchased from an aquarium store. The amount of activated carbon necessary for each chromatography column was previously washed with water to eliminate dust and stored in vials to minimize manipulation by the students. Grenadine syrup (containing Carminic acid-E120) or liquid food coloring (red-Azorubine-E122, yellow-Tartrazine-E102 or blue-Brilliant Blue FCF-E133) available in food stores can be used as the colored solution. Either a solution of grenadine syrup in tap water (1/1 in volume), or 2 drops of food coloring added to 200mL of tap water, was prepared.

FINAL DEBRIEFING AND CONCLUSION

At the end of the activity, the students were asked to tell what they had learned from the experiments. Through this first oral evaluation, we noticed that they understood well that two

materials made of the same element can have different properties (macroscopic scale) due to their solid state arrangement (microscopic scale). They also explored separation techniques using the adsorption properties of activated carbon. This activity developed manual skills and collaboration during the experiments. As mentioned in the description of the activity, the teacher continued the activity during other science courses. In addition to the documents filled during the activity, each student wrote a personal report. The teacher helped the students understand how to choose among the observations in order to draw conclusions using appropriate vocabulary. They also presented their work orally to their school mates in the form of a poster exhibition.

The activity proposed on carbonaceous materials has been built to answer the skills recommended by the program of Cycle 3 in science and technology¹². It offers ideas that any teacher of other countries can use in their class. The relationship between experiments and skills is as follows:

- The access to experiments based on known materials and the use of simple equipment allows students *“understanding the world around us”*. They *“acquire the scientific languages necessary to analyze the observations and experiments”* by filling the student worksheets. They write personal reports and draw schemes of the experiments *“to describe their observations using texts and diagrams”*;
- The geological timescale of the student worksheet allows *“acquiring temporal benchmarks”*. The construction of the hexagonal sheets of graphite and tetrahedral structures of diamond and their associations in three directions to figure out the material, agree with *“conduct experimental approach to acquire spatial benchmarks and notions of scale”*;
- The macroscopic properties of graphite and diamond (color, hardness) are easy to list by the students to *“describe the state and constitution of matter on a macroscopic scale”*;
- The experiments with conductivity and adsorption help the students to identify electrical conductors, insulators and adsorbent materials as *“main families of materials”* and to classify them *“according to their physical and chemical properties”*.

ASSOCIATED CONTENT

Supporting Information (after references)

File1: Teacher-student worksheets.

File 2: Templates to build the hexagonal and tetrahedral carbon arrangements; equipment for conductivity and adsorption experiments; general poster of the activity.

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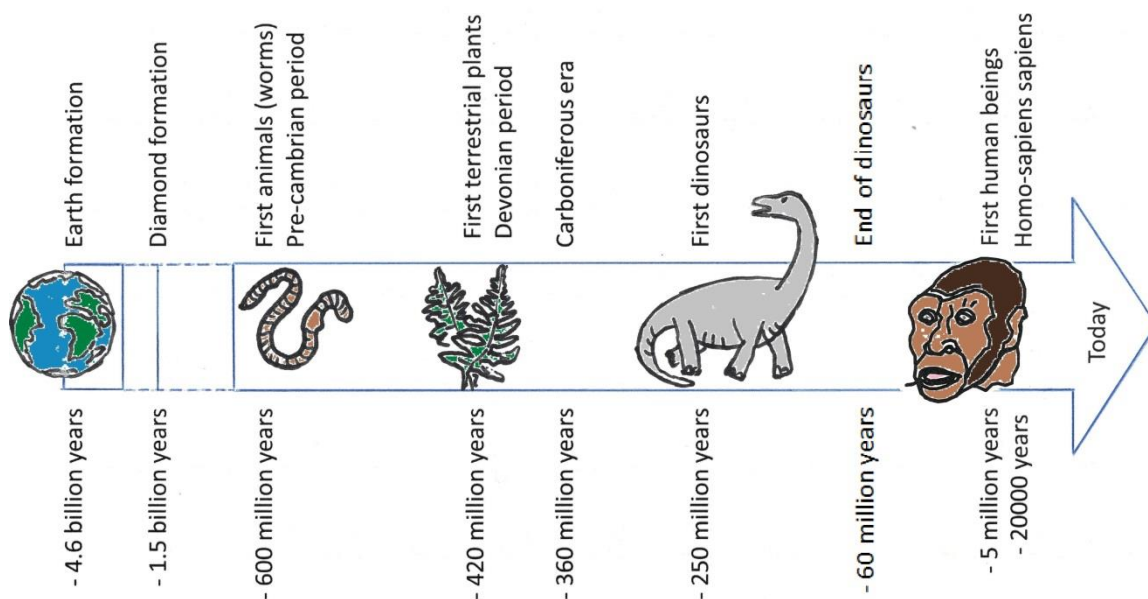
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TEACHER WORKSHEET FOR THE ACTIVITY

This form can be used when the activity is conducted in class. The blank student form for duplication is at the end of the document.

GEOLOGICAL TIME SCALE



The age of earth is [4.6 billion](#) years.

Coal formation started [360 million](#) years ago.

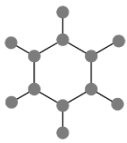
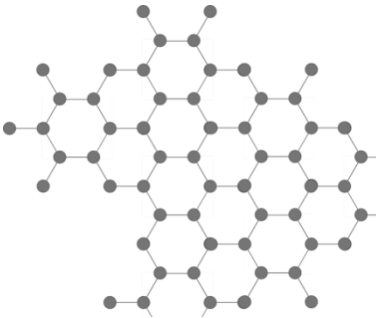
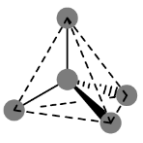
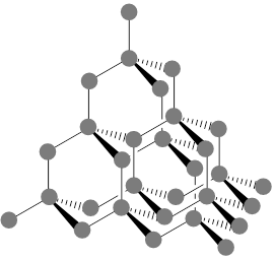
Coal results from the slow decomposition of [plants](#).

Diamond formation is *[older/younger](#) than coal formation.

First human being appeared [5 million](#) years ago.



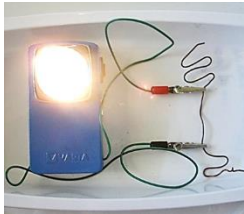
* *Cross out the wrong answer*

COMPOSITION AND PROPERTIES OF COAL AND DIAMOND

Property	Coal	Diamond
Organization of carbon atoms	 <p style="text-align: center;"><u>Hexagon</u></p> <p>Within one layer, each carbon atom has <u>3</u> neighbors. Hexagonal pavement in graphite.</p> 	 <p style="text-align: center;"><u>Tetrahedron</u></p> <p>Each carbon atom has <u>4</u> neighbors. Tetrahedrons organization in diamond.</p> 
Hardness	In coal, graphite hexagonal layers, named graphene, are piled with gas between layers and they can slip one over the other; coal is <u>*soft / hard</u> .	In diamond all carbon atoms are strongly attached in all directions; diamond is <u>*soft / hard</u> .
Color	Carbon atoms have 4 electrons available to connect to other carbon atoms; in graphite, they only use 3 of them. The remaining electrons form a cloud that adsorbs light; coal is <u>black</u> .	Carbon atoms use all their 4 electrons to connect to other carbon atoms. Light goes through diamond without being stopped; diamond is <u>transparent</u> .
Conductivity	The cloud of electrons can transport electricity; coal is <u>conductive</u> .	In diamond no electrons are available to conduct electricity; diamond is <u>insulating</u> .



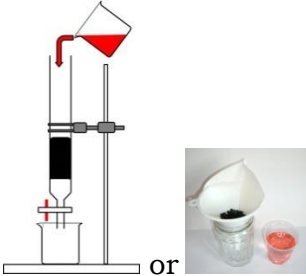
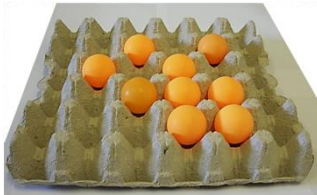
* *Cross out the wrong answer*

CONDUCTIVITY OF GRAPHITE: I LIGHT A BULB

Experiment	Wood chopstick	Pencil	Copper wire
Connect clips to each material, draw the circuit and observe light bulb	Light * ON / OFF 	Light * ON / OFF 	Light * ON / OFF 
Electrical property	The material does not conduct electricity; it is * conductive / <u>insulating</u>	The material conducts electricity; it is * conductive / <u>insulating</u>	The material conducts electricity; it is * conductive / <u>insulating</u>
Explanation	Wood is made of organic matter that does not conduct electricity.	The pencil contains graphite type carbon powder which conducts electricity and clay which is insulating.	Copper is a metal and better conducts electricity than the mixture of graphite and clay. The bulb shines * more / <u>less</u> than with the pencil.

* *Cross out the wrong answer*

ADSORPTION PROPERTIES OF ACTIVATED CARBON: I DISCOLOR GRENADINE

Experiment	Water	Water + grenadine	Water + grenadine passed over activated carbon
Add color where needed			
What is the color of the liquid?	Water is <u>colorless</u> .	When I add grenadine, the liquid is <u>pink</u> .	After passing over activated carbon, the liquid is <u>colorless</u> .
Explanation	The liquid only contains <u>water</u> .	The color is due to a <u>dye</u> contained in grenadine.	Activated carbon traps the dye. Only water goes through. This phenomenon is called <u>adsorption</u> . The surface of activated carbon resembles an egg box. The dye is trapped in the holes. 

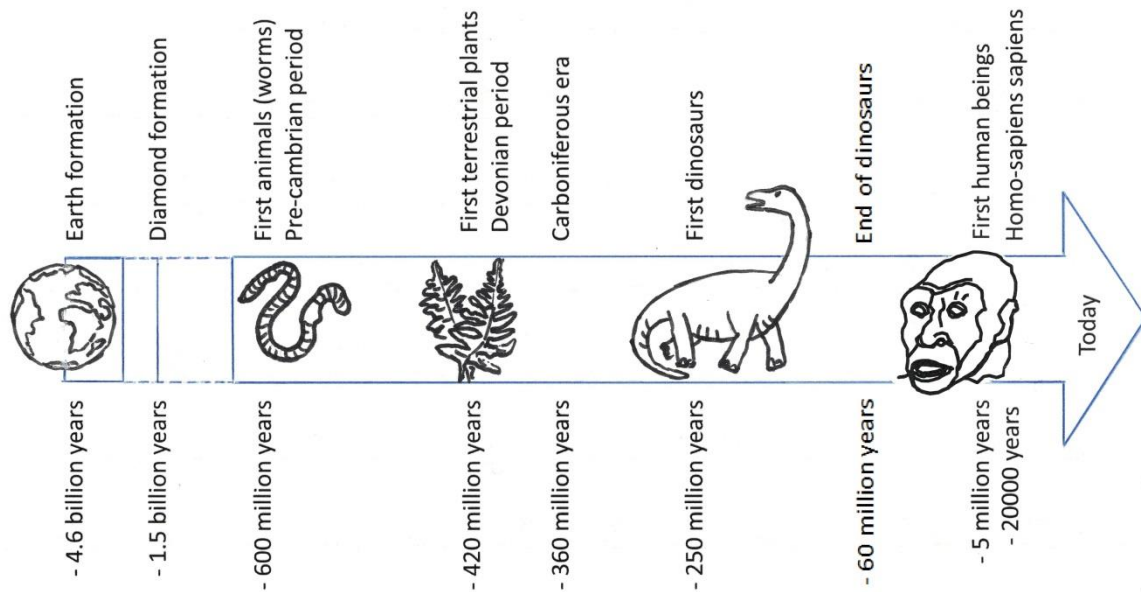
Carbonaceous materials: Construction of graphite and diamond and experiments with electrical and adsorption properties

Lydie Valade, Jean-Louis Pellegatta, Myriam Dubreuil and Laurence Toral

STUDENT WORKSHEET FOR THE ACTIVITY

This form can be used when the activity is conducted in class.

GEOLOGICAL TIME SCALE



The age of earth is _____ years.

Coal formation started _____ years ago.

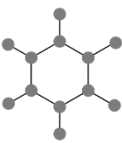
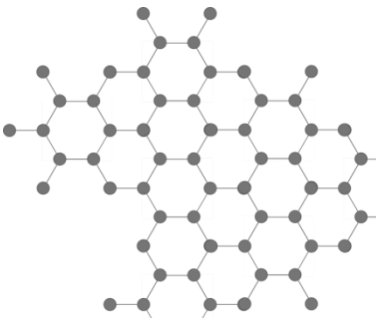
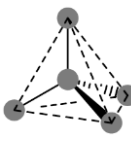
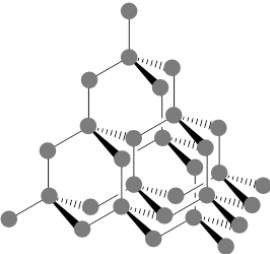
Coal results from the slow decomposition of _____.

Diamond formation is *older/younger than coal formation.

First human being appeared _____ years ago.

* *Cross out the wrong answer*

COMPOSITION AND PROPERTIES OF COAL AND DIAMOND

Property	Coal	Diamond
Organization of carbon atoms	 <p style="text-align: center;">_____.</p> <p>Within one layer, each carbon atom has <u> </u> neighbors. Hexagonal pavement in graphite.</p> 	 <p style="text-align: center;">_____.</p> <p>Each carbon atom has <u> </u> neighbors. Tetrahedrons organization in diamond.</p> 
Hardness	In coal, graphite hexagonal layers, named graphene, are piled with gas between layers and they can slip one over the other; coal is <u>*soft / hard</u> .	In diamond all carbon atoms are strongly attached in all directions; diamond is <u>*soft / hard</u> .
Color	Carbon atoms have 4 electrons available to connect to other carbon atoms; in graphite, they only use 3 of them. The remaining electrons form a cloud that adsorbs light; coal is _____.	Carbon atoms use all their 4 electrons to connect to other carbon atoms. Light goes through diamond without being stopped; diamond is _____.
Conductivity	The cloud of electrons can transport electricity; coal is _____.	In diamond no electrons are available to conduct electricity; diamond is _____.



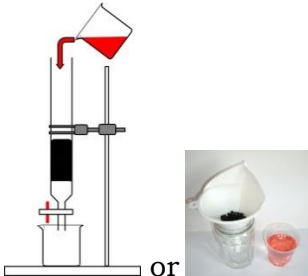

* *Cross out the wrong answer*

CONDUCTIVITY OF GRAPHITE: I LIGHT A BULB

Experiment	Wood chopstick	Pencil	Copper wire
Connect clips to each material, draw the circuit and observe light bulb	Light * <u>ON / OFF</u>	Light * <u>ON / OFF</u>	Light * <u>ON / OFF</u>
Electrical property	The material does not conduct electricity; it is * <u>conductive / insulating</u>	The material conducts electricity; it is * <u>conductive / insulating</u>	The material conducts electricity; it is * <u>conductive / insulating</u>
Explanation	Wood is made of organic matter that does not conduct electricity.	The pencil contains graphite type carbon powder which conducts electricity and clay which is insulating.	Copper is a metal and better conducts electricity than the mixture of graphite and clay. The bulb shines * <u>more / less</u> than with the pencil.

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ADSORPTION PROPERTIES OF ACTIVATED CARBON: I DISCOLOR GRENADINE

Experiment	Water	Water + grenadine	Water + grenadine passed over activated carbon
Add color where needed			
What is the color of the liquid?	Water is _____.	When I add grenadine, the liquid is _____.	After passing over activated carbon, the liquid is _____.
Explanation	The liquid only contains _____.	The color is due to a _____. contained in grenadine.	Activated carbon traps the dye. Only water goes through. This phenomenon is called _____. The surface of activated carbon resembles an egg box. The dye is trapped in the holes. 

A classroom activity on carbonaceous materials: Construction of graphite and diamond and experiments with electrical and adsorption properties

Lydie Valade, Jean-Louis Pellegatta, Myriam Dubreuil and Laurence Toral

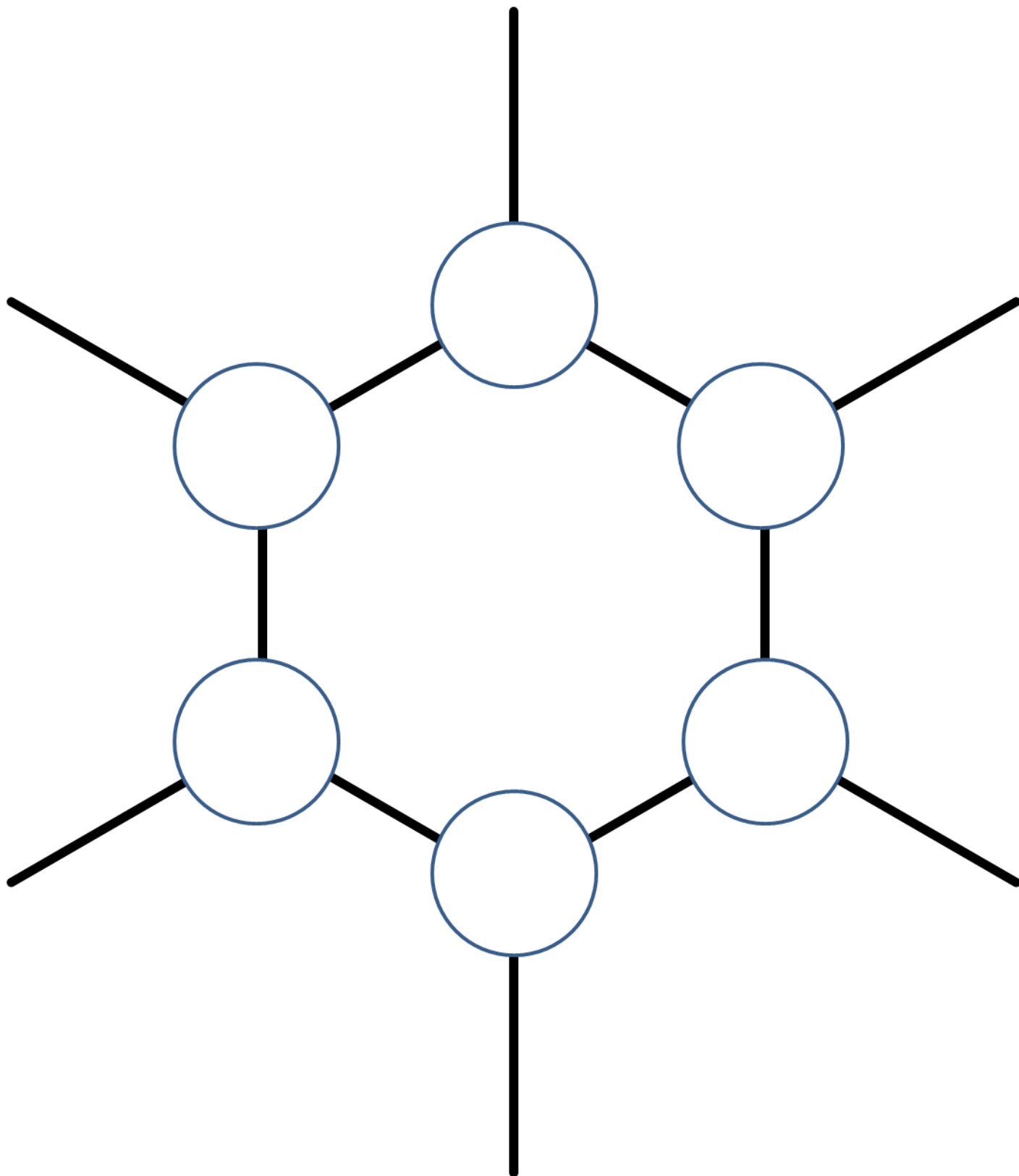
SUPPORTING INFORMATION

CONTENT

1. TEMPLATE TO BUILD THE HEXAGONAL STRUCTURE OF GRAPHITE
2. TEMPLATE OF THE SUPPORT TO BUILD THE TETRAHEDRAL ARRANGEMENT OF DIAMOND STRUCTURE
3. STUDENTS CONSTRUCTIONS OF GRAPHITE AND DIAMOND STRUCTURES
4. EQUIPMENT FOR CONDUCTIVITY
5. PREPARATION OF THE COLUMN AND ADSORPTION EXPERIMENT
6. ALTERNATIVE EQUIPMENT AND ILLUSTRATION FOR EXPLAINING ADSORPTION
7. POSTER OF COAL ACTIVITY

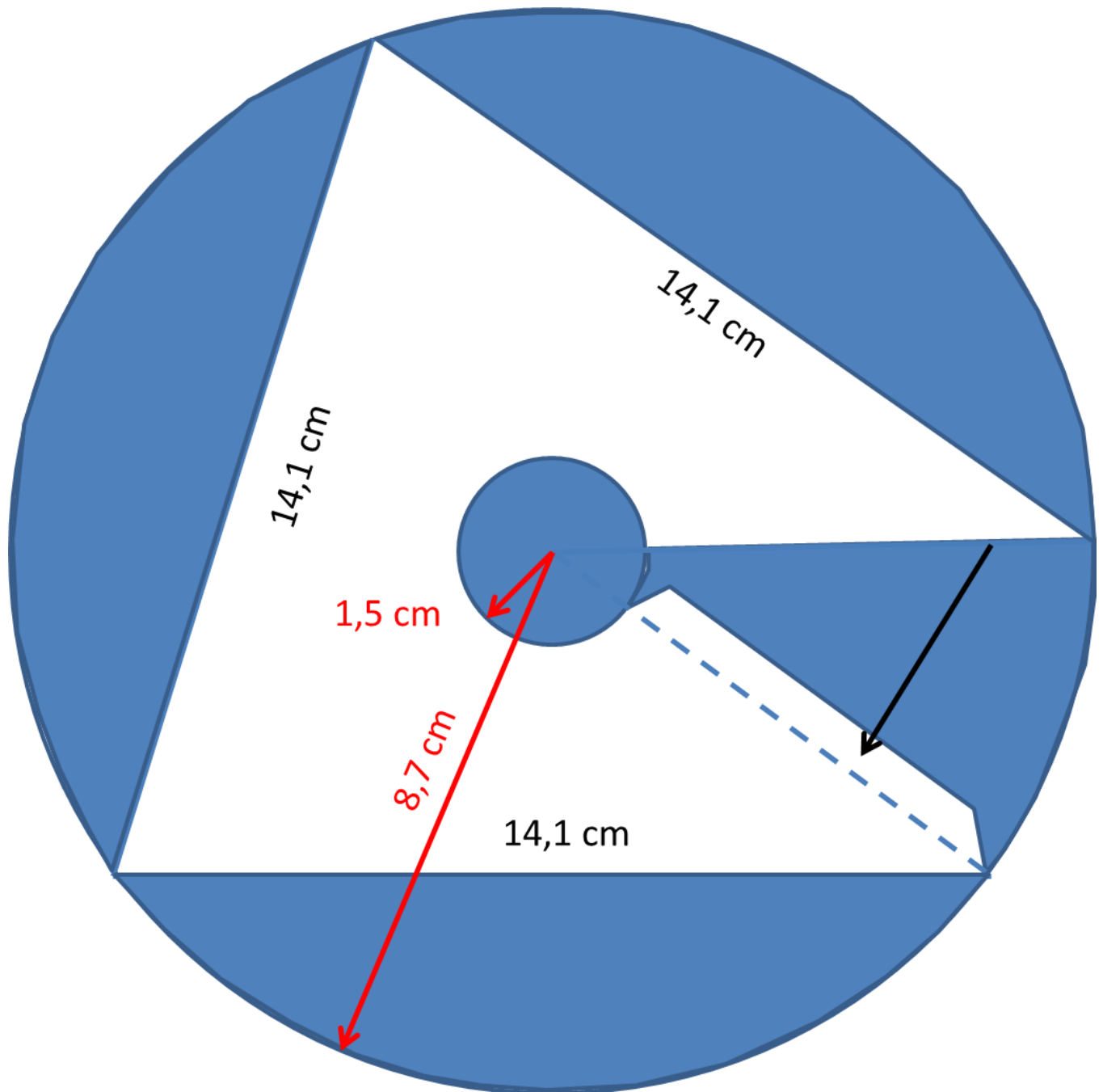
TEMPLATE TO BUILD THE HEXAGONAL STRUCTURE OF GRAPHITE

Use this template to assemble polystyrene balls with toothpicks.

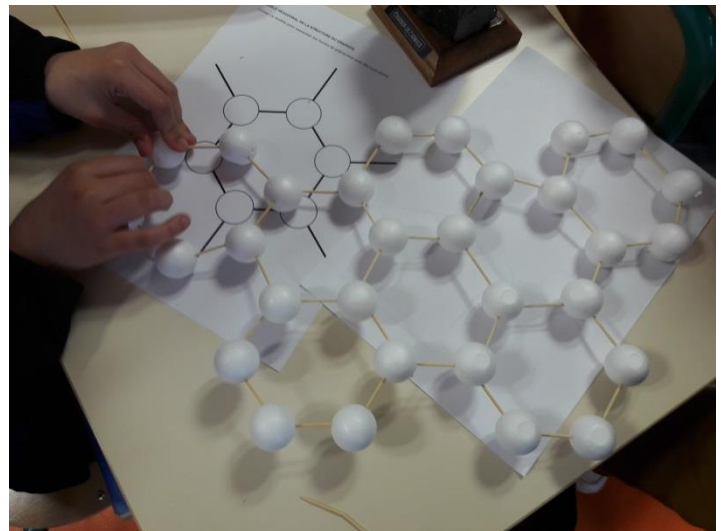
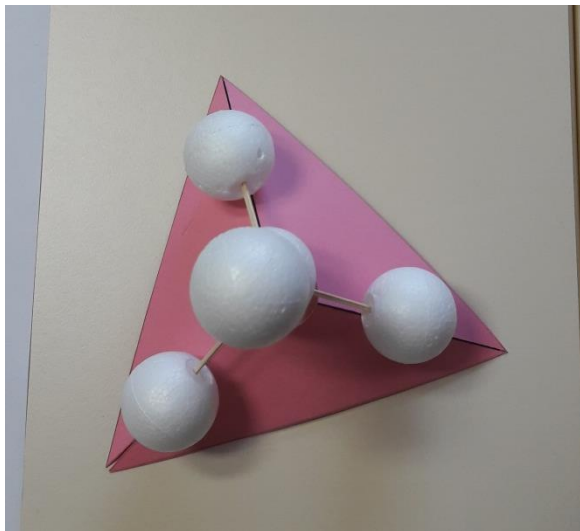
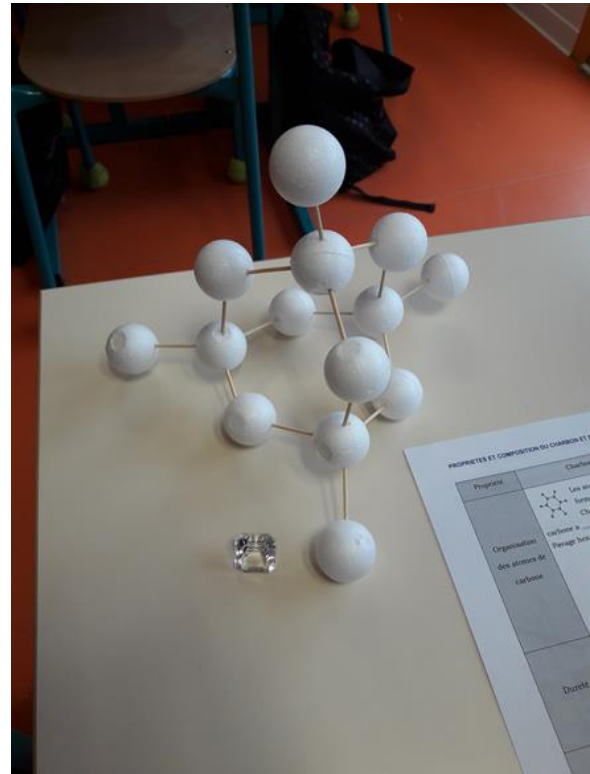
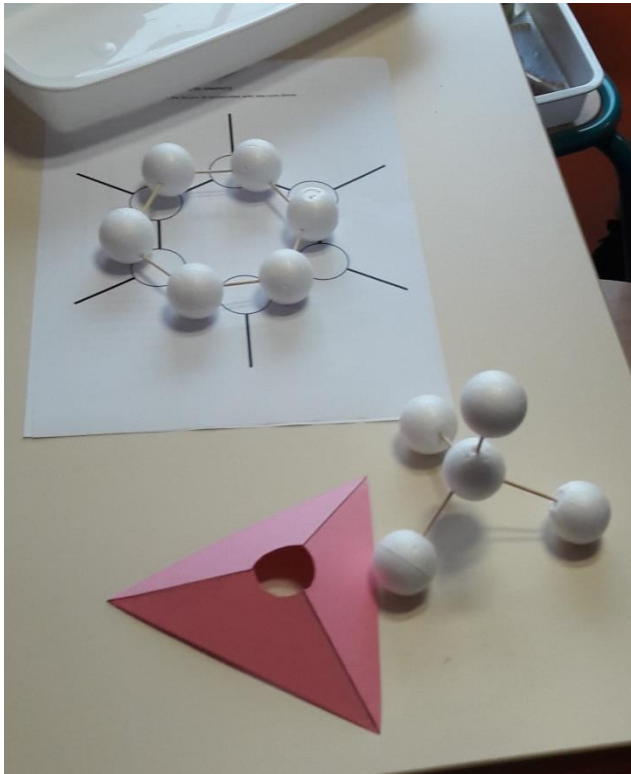


TEMPLATE OF THE SUPPORT TO BUILD THE TETRAHEDRAL ARRANGEMENT OF DIAMOND STRUCTURE

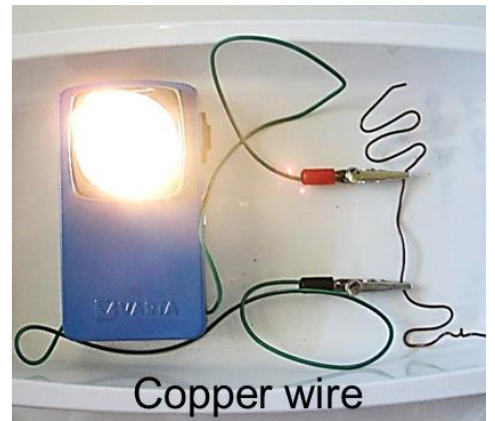
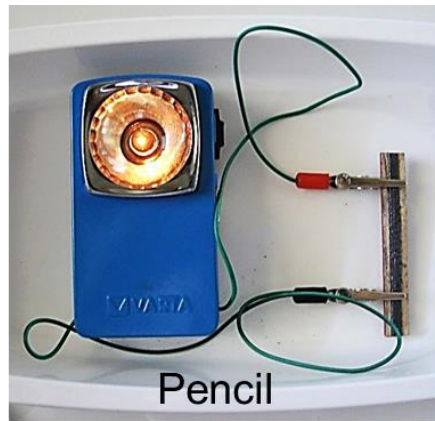
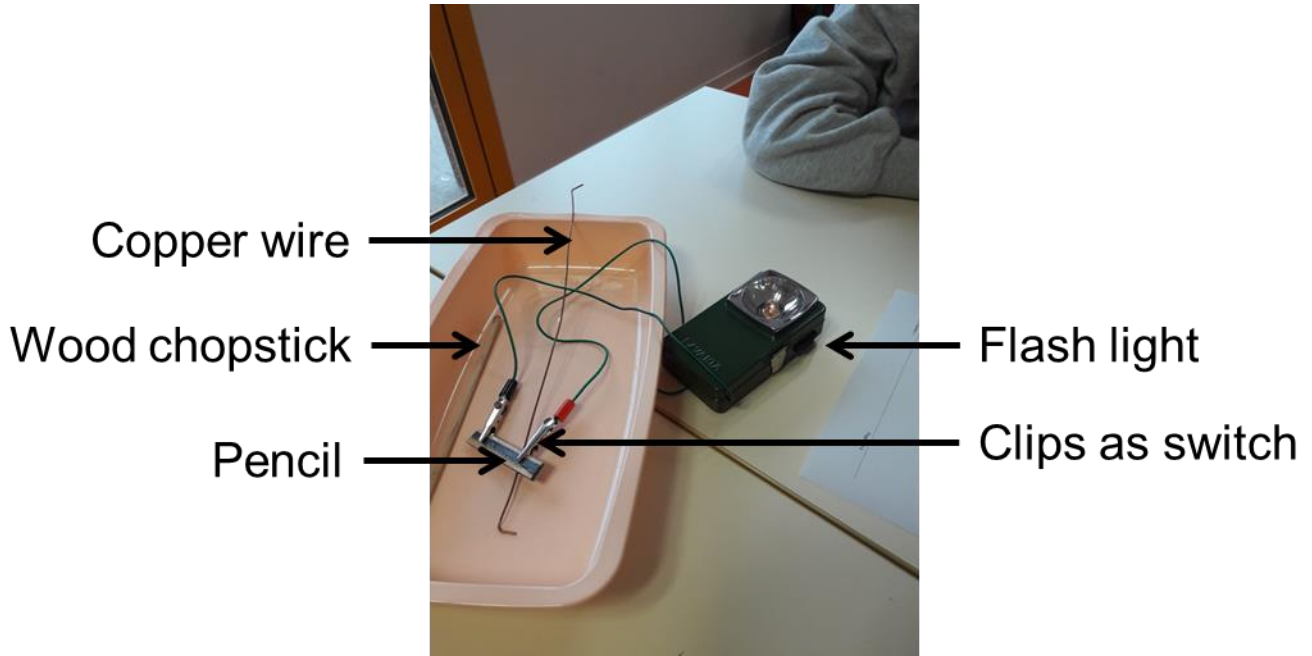
The size of the support is designed for 3 cm polystyrene balls and allows respecting the angle of $109^{\circ}28'$ between each bond.



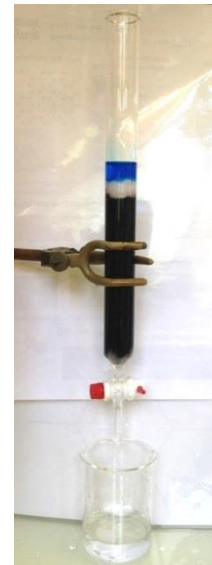
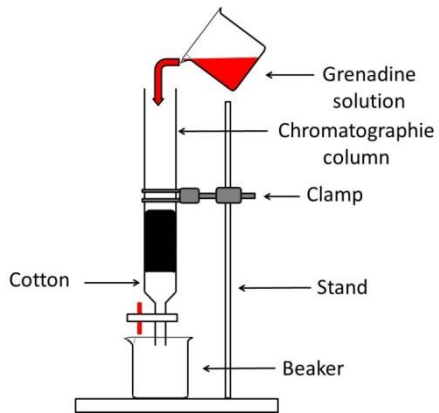
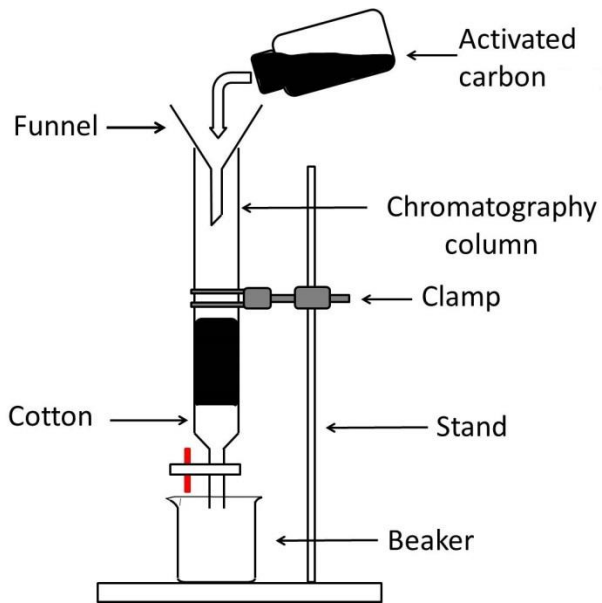
STUDENTS CONSTRUCTIONS OF GRAPHITE AND DIAMOND STRUCTURES



EQUIPMENT FOR CONDUCTIVITY

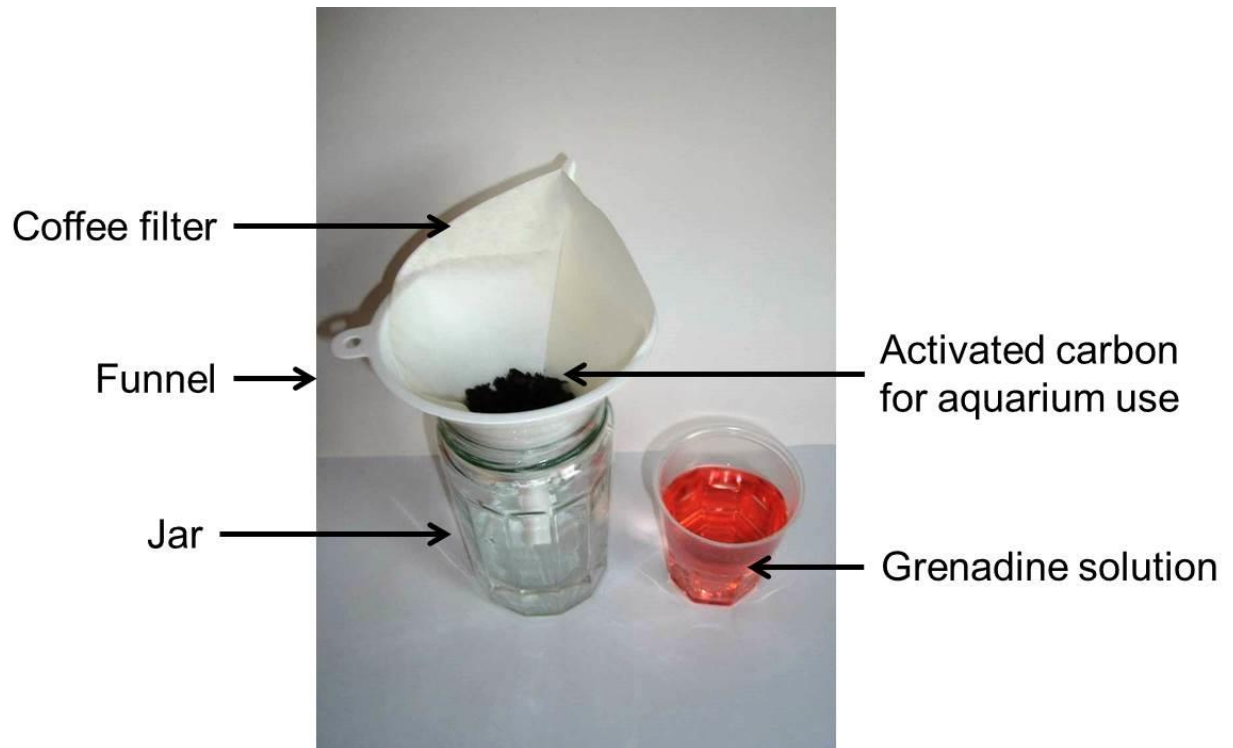


PREPARATION OF THE COLUMN AND ADSORPTION EXPERIMENT



Adsorption using a grenadine solution or a blue food coloring

ALTERNATIVE EQUIPMENT AND ILLUSTRATION FOR EXPLAINING ADSORPTION



Egg box and ping-pong balls

I LIGHT A BULB - I DISCOLOR GRENAADINE



COAL FORMATION



Sedimentation
of plants



Peat



Lignite



Anthracite



COALIFICATION DURATION AND CARBON CONTENT

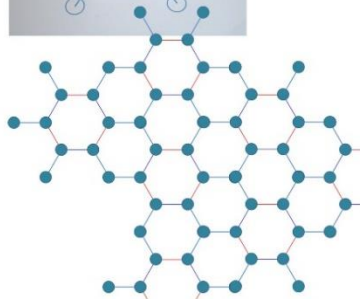
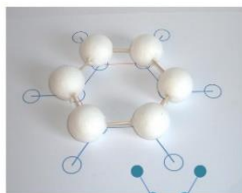
Peat 50% C < 10000 years	Lignite 65-75% C 65 millions years	Coal 80-90% C 300-500 millions years	Anthracite 95% C	Graphite 100% C
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Carbon content (increasing from left to right)

Water content (decreasing from left to right)

PROPERTIES OF GRAPHITE CONTAINING MATERIALS

Coal contains
graphite carbon



Hexagonal paving in graphite

Graphite conducts **electricity**



Wood chopstick
Light off



Graphite pencil
Light on



Copper wire
Light on

The more the matter conducts,
the more the bulb shines

Activated carbon
adsorbs dyes



Adsorption



www.chimieetsociete.org

