Quantum jewels: crafting colorful diamonds and graphene with marshmallows

We will use marshmallows and toothpicks to construct various crystal structures, including diamond, and make them glow by incorporating colorful marshmallows. This activity will introduce the concept of solid-state quantum defects, which are imperfections in crystals that give them color and have applications in quantum sensing, communication, and computing.

Learning outcomes
- Identify the structure of diamond and graphene based on their dimensionality (2D vs 3D) and the arrangement of carbon atoms in the material
- Relate atomic defects in the crystal structure to the emission color of the material
- Discuss applications of diamond and graphene in quantum science and technology

Materials
- Mini marshmallows (white and an assortment of colors)
  - To make a diamond crystal model, you will need a minimum of 14 marshmallows.
  - To make a graphene unit cell, you will need 6 marshmallows.
- Toothpicks (preferably broken in half)
  - To make a diamond crystal model, you will need a minimum of 14 half-length toothpicks.
  - To make a graphene unit cell, you will need 6 half-length toothpicks.

Background knowledge
Diamond color centers: A diamond is a crystal in which the carbon atoms are arranged in a very strong lattice structure. Imagine a 3D grid where each point of intersection has a carbon atom. This rigid structure is what gives diamonds their incredible hardness and clarity. Each carbon atom is bonded to four other carbon atoms in a tetrahedral configuration, forming a repeating pattern that extends in all directions. Diamond crystals can take on different colors when one of the carbon atoms is replaced by a different type of atom, or a defect. This defect interrupts the regular arrangement of carbon atoms and can absorb and emit light, which often gives the diamond a particular color. These color centers are not just about aesthetics; they have unique electronic and optical properties that are of interest for various quantum applications, including the use of the light emitted from diamond to measure very small magnetic fields (quantum sensing) and to encode and transport secure information (quantum communication).

Graphene: Graphene is a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Picture a flat sheet made up of hexagons, similar to a honeycomb, where each corner is a carbon atom bonded to three other atoms. This structure makes graphene incredibly strong, even stronger than diamond, and yet it is remarkably flexible and lightweight. Graphene is also an excellent conductor of
electricity and heat. Finally, graphene is atomically thin, which makes it an effective material for studying quantum effects involving the transport of electrons.

**Activities:**
We will assemble models for diamond and graphene by using marshmallows of the same color to represent carbon atoms and connect them with (half-length) toothpicks to represent the bonding between the atoms. We will then substitute a marshmallow in the crystal with another one of a different color to incorporate a “color center”, which will make the crystal glow colorfully.

**Diamond color centers**
In a diamond crystal, each carbon atom is bonded to four other carbon atoms. The bonds form a tetrahedral structure, in which each carbon sits at the center of the tetrahedron with four other atoms at the corner.

1. Assemble 3 tetrahedron, shown below, with each involving a single carbon atom (marshmallow at the center) and toothpicks pointing into the directions where the adjacent carbon would be:

2. Add marshmallows to each tetrahedron, to make the units labeled “A”, “B”, and “C” below:
   i. For “A”, add a marshmallow to each of the three legs.
   ii. For “B”, add a marshmallow to two of the three legs.
   iii. For “C”, add a marshmallow to only one of the three legs.
3. Connect “A” and “B” together such that the unpaired leg from “B” is connected to one of the marshmallows in “A”, as shown below:

![Diagram of A and B connected](image1)

4. Add “C” to the composite structure by connecting each of its unpaired legs to a marshmallow from “A” and “B” as seen below. If you look at the structure from the top, you should be able to recognize a hexagon or honeycomb shape (see shaded region).

![Diagram of A, B, and C](image2)

5. Let the structure dry out for at least an hour (ideally overnight), so that it becomes more rigid.

6. Add a marshmallow to the top of each tip as shown below.

![Diagram with marshmallows on top](image3)

7. Assemble a new tetrahedron and add it to the structure:
8. To complete this diamond structure, add a marshmallow to the top. Note that you should be able to spot the hexagon/honeycomb structure by looking at the structure from the side.

9. Now you can substitute any one (or more) of the marshmallows in the structure to give the diamond crystal color!

Graphene
Graphene is a single layer of carbon atoms arranged in a two-dimensional plane, forming a pattern that looks like a hexagon or honeycomb.

1. Assemble a hexagon comprising of 6 marshmallows and 6 toothpicks on a single layer.
2. Connect additional honeycomb structures on that same layer, as follows:

3. You can also substitute any one (or more) of the marshmallows in the structure to introduce defect(s) in the graphene which can make it emit light!