Station 1

During this station, we'll examine some of the assumptions that underlie Kinetic Molecular Theory, the framework for our understanding of ideal (and real!) gases.

1. Consider a small amount of gas held in a container with a movable piston (i.e. the volume of the container can change) that is kept at constant temperature throughout all parts of this question.
   (a) Since temperature is held constant, this process is best described as (isothermal/isobaric).
   (b) As the piston is pulled outwards, the volume of the container increases. What happens to the pressure of the gas inside the container?
   (c) Which Gas Law best represents the relation described in the part above? Choose from Boyle's Law, Charles' Law, and Gay-Lussac's Law.
   (d) As the volume increases, do you expect the behavior of the gas to become more ideal or less ideal? Explain your answer in detail.

2. One of the principal assumptions is that the particles of the gas are of negligible volume compared to the size of their container. Let's examine how realistic this assumption is for a non-ideal (i.e. real) monatomic gas.
   (a) What does "monatomic" mean? Is N_2 an example of a monatomic compound?
   (b) Consider a rigid container that has a volume of 1 m^3 when it is empty. 1 mol of helium gas is placed in the container. What fraction of the container's volume is taken up by the volume of all of the individual helium atoms? A helium atom has an atomic "radius" of 140 pm, where 1 pm = 10^{-12} m. *Hint: find the volume of one atom, assuming it is a sphere. Then, multiply it by Avogadro's number to find the total volume of all of the helium atoms. Divide the total volume of all of the atoms by the volume of the container, 1 m^3.*

3. Another core assumption of Kinetic Molecular Theory is that the molecules in a gas have no intermolecular forces (i.e. they do not interact with each other at all). Consider two identical, rigid containers at the same temperature. Container A holds 1 mol water vapor, while Container B golds 1 mol helium gas.
   (a) In a real gas, where intermolecular forces cannot be neglected, do we expect intermolecular forces to be more impactful at high temperatures or low temperatures? Explain your answer.
   (b) Between water vapor and helium, which has stronger intermolecular forces? Explain your answer.
   (c) Which container would you expect to be experiencing a higher pressure from the gas inside? Explain your answer.
   (d) A student says that assuming that there are no intermolecular interactions between gas molecules is redundant with saying that the molecules of the gas are of negligible volume compared to the size of their container. Connect these two ideas.

Station 2

Solutions!

4. You are the event supervisor for Water Quality at a local Science Olympiad tournament and need to make several salt water solutions using NaCl.
   (a) How many grams of salt must be added to 500 mL of water to make a solution that is 5.0% salt by mass?
   (b) How many moles of salt are needed for the situation described in part (a)? The molar mass of Na is 22.99 g/mol and the molar mass of Cl is 35.45 g/mol.
   (c) How many grams of salt must be added to 500 mL of water to make a 2500 ppm solution?
   (d) What is the concentration, in ppb, of a solution made from 450 mL of water and 0.0010 g of salt?

5. Solution 1 has a density ρ_1 and a volume V_1 and Solution 2 has a density ρ_2 and volume V_2. When both of these solutions are mixed together, they form a new solution.
   (a) What is the density of the final solution, in terms of ρ_1, ρ_2, V_1, and V_2? Assume that the volumes are additive.
   (b) Suppose that the temperature of the final solution is increased. How might we expect the density of the final solution to change? Explain your answer.

6. 10.0 grams of an unknown substance are dissolved in water at 20°C to make a saturated solution with a volume of 5 mL. Analytical techniques show that the unknown substance has a molar mass of 40 g/mol.
   (a) How many moles of the unknown substance were dissolved? *Hint: divide the mass by the molar mass to get moles.*
   (b) What is the concentration, in mol/L, of the solution?
   (c) A student notices that if the solution is heated to 30°C, then 60 grams of the unknown substance can be dissolved. Based on this observation, do you expect the process of this substance dissolving to be an endothermic (heat absorbing) or exothermic (heat releasing) process?

Station 3

Interstellar space has an average number density (n) of roughly 1 hydrogen atom per cubic centimeter and a temperature (T) on the order of 10 Kelvin. In this station, we'll examine this sliver of astrophysics from a Density Lab perspective.

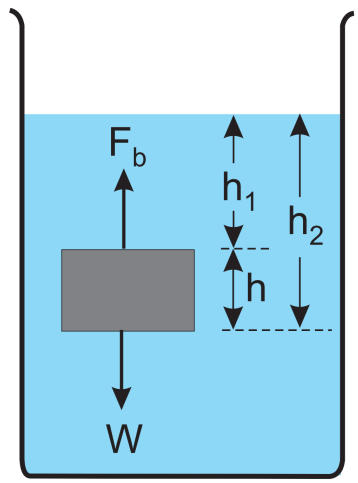
7. Let's begin by calculating some of its basic properties. For this question, assume that the hydrogen atoms are an ideal gas.
   (a) Conceptually, why is it reasonable to assume ideal behavior, even though the temperature is so low? Explain in detail.
   (b) What is the mass density, in kg/m^3, of interstellar space? A hydrogen atom has a mass of 1.67×10^{-27} kg.
   (c) What is the molar volume, in L/mol, of interstellar space?
   (d) What is the pressure, in Pa, of interstellar space?

8. In this question, suppose that each hydrogen atom is a solid sphere with radius r that cannot be deformed.
   (a) What is the cross-sectional area, σ, of a single hydrogen atom? Give your answer in terms of π and r. *Hint: this is just the area of a circle.*
   (b) Suppose that the average velocity of these hydrogen atoms is $\langle v \rangle$. What is the volume "swept out" by a single atom during a time t, in terms of σ, $\langle v \rangle$, and t? *Hint: this is the volume of a cylinder with base of area σ and a length equal to the distance the atom would travel in a time t.*
   (c) Based on your answer to the previous part, what is the mean free path, l, for a single hydrogen atom? The mean free path represents the average distance a hydrogen atom will travel between collisions and therefore has dimensions of length. *Note: This part is especially challenging - if you're having trouble with this part, it might be worth your time to work on other parts of the station.*

9. Suppose that we magically isolate a bit of interstellar space with 100 hydrogen atoms in it so that nothing can move in or out of this space.
   (a) Given the number density, n, given in the description for this station, how large, in cubic meters, would this volume be?
   (b) What is the probability that these 100 hydrogen atoms will spontaneously contract the volume they collectively occupy by 5%? If your calculator is having trouble computing this value, feel free to leave it in an unsimplified form. *Note: this is <u>not</u> talking about the volume of the individual atoms themselves.*

Station 4

Legend states that Archimedes ran naked through the streets shouting "Eureka!" after discovering what's now known as Archimedes' Principle. In this station, we'll take a closer look at it. The diagram below shows an object (a rectangular prism with density ρ_o) in equilibrium and submerged completely in a fluid (with density ρ_f), with other quantities labeled on the figure itself.

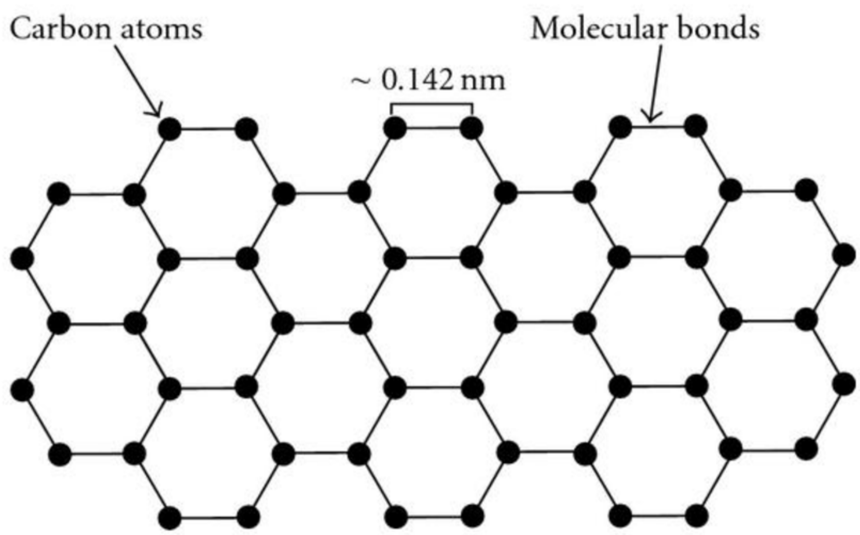


10. Before we begin, a couple of conceptual checks:
    (a) A cylinder with a radius of 2 cm and a height of 10 cm has a mass of 100 grams. What is its density, in grams per cubic centimeter?
    (b) The cylinder in part (a) is placed in a tank of water. What percentage of the cylinder would be below water? If the cylinder would sink, answer with "100%".
    (c) Consider two objects that are both completely submerged in a fluid. Both have the same volume, but one object is twice as dense as the other. Are the buoyant forces on these two objects different or the same? Explain why.
    (d) If I cut a block of wood in half, what happens to the density of the two pieces? Is the density different from the original block of wood?
    (e) What is the difference between gauge pressure and absolute pressure? Explain in one sentence or less.
11. This question directly pertains to the diagram above.
    (a) What is the mass of the fluid directly above the top face of the object? Assume that the top face has an area of A. Give your answer in terms of ρ_f, g, h_1, and A.
    (b) What is the gauge pressure in the fluid at a depth of h_2? What about at h_1? Give your answer in terms of ρ_f, g, and h_1 or h_2.
    (c) Knowing that the buoyant force is the difference between the force pushing up on the bottom of the object and the force pushing down on the top of the object, write an expression for the buoyant force on this object. Give your answer in terms of ρ_f, g, h, and A. Note that $h = h_2 - h_1$.
    (d) Your answer for part (c) should be independent of the external pressure of the atmosphere. Briefly explain why.

Station 5

This station consists of a hands-on portion in which you'll make graphene using nothing more than some pencil lead and tape! Graphene is a form of carbon in which carbon atoms are arranged in a flat, hexagonal lattice as shown below. When many layers of graphene are stacked on top of each other, you get graphite, the material used in pencil lead.

Instructions for hands-on activity: Begin by drawing a very dark scribble on a piece of paper with one of the provided pencils. This will deposit a thick layer of graphite. Then, cut a 5 cm piece of tape and place it on the graphite. Press the tape down and gently peel it off the paper. Grasp the tape on the edges and only fold it enough to cover the graphite. If you fold it completely in half, it will be difficult to open it up and pull it apart again. Repeat the process of folding and peeling 10 times. When you are done, place your piece of tape on the bottom third of your answer sheet for this station (<u>not</u> on this station itself).



12. (a) As you keep folding and peeling, what happens to the color/opacity of the graphite on the tape?
    (b) What is the folding/peeling doing to the graphite?

13. In this question, we'll determine what the area density (mass per unit area) of graphene is, assuming that we are only dealing with a single layer. Recall that the mass of a carbon atom is 1.99×10^{-23} grams, the length of a carbon-carbon bond is 0.142 nm, and that the area of a regular hexagon with side length a is $1.5\sqrt{3} \times a^2$.
    (a) What is the area of each hexagon, in square meters?
    (b) Each carbon atom is shared between how many hexagons?
    (c) Based on your answer to the previous part, what is the mass, in mg, of each hexagon?
    (d) Using your answers from parts (a) and (c), what is the area density of graphene, in mg per square meter?