Teachers' Guide: Magic Sand®/Magic Water

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Chemical Concepts

Magic Sand can be used in simple demonstrations that are remarkably memorable to students[1,2,3,4,5]. It is available from several suppliers[6]. It serves as a concrete exemplar for a variety of concepts, but students may be stimulated most by starting with a quick Magic Sand demonstration and discussion of biogenesis, and using it as a motivator to learn the other concepts:

- Solubility and the hydrophobic effect
- Structure and properties of water
- Free Energy/Entropy
- Reverse phase high performance liquid chromatography (HPLC)
- Biogenesis: The origins of life

A recent review article[7] lists the areas where understanding the hydrophobic effect and the structure of water are important: membrane and micelle formation, protein folding, ligand-protein and protein-protein binding, chromatographic retention, possibly nucleic acid interactions, and the partitioning of drugs.

How the Demonstration Addresses Concepts

Solubility and the hydrophobic Effect: When Magic Sand is added to water, it appears to bond to itself, forming interesting shapes. But when the water is decanted, the sand is dry, and the shapes disappear. The shapes were created by the water, as a result of strong intermolecular bonds between polar water molecules[8]. The "magic" is in the water, not in the sand.

The insolubility of nonpolar oil in polar water is not as simple as it seems. Although oil and water don't mix (vinegar/oil salad dressing proves that!), it's not because oil molecules are not attracted to water molecules. A drop of oil on the surface of a lake spreads out into a layer whose beautiful iridescence shows that its thickness is sometimes similar to the wavelength of light. It may, in fact, be only a molecule thick, indicating that the oil bonds to the water surface better than it bonds to itself. The interaction is actually exothermic! Lord Rayleigh made one of the first determinations of the size of a molecule in 1890, assuming that oil forms a monolayer on water.

So why can't the oil dissolve (be completely surrounded by water), rather than having water on just one side? Because there would be a decrease in entropy of vicinal[10] water molecules under the influence of the oil droplet. The resulting expulsion or encapsulation of nonpolar substances by water is called the "hydrophobic effect".

Structure and Properties of Water: Magic Sand reveals the "magic" in water, or more scientifically, the incredible properties of this small molecule[9,10]. Due to its strong hydrogen bonding, water forms a confining sheath around Magic Sand without touching it, as the bubble-like appearance of the Magic Sand structures suggests. This may be proven by floating Magic Sand on 150 ml of saturated potassium carbonate solution in a 250 ml beaker, then adding 6M H_2SO_4 dropwise to the surface of the Magic Sand until a globule of Magic Sand-coated sulfuric acid sinks to the bottom. No reaction occurs across the Magic Sand barrier, but if a spatula is used to break it, fizzing immediately occurs. This is an interesting model for liposomes, which are manufactured on an industrial scale by ultrasound treatment of phosopholipid/water suspensions, and used as vehicles for cosmetics and drugs. Liposomes allow only very nonpolar substances (often lipophilic antitumor drugs) to penetrate their bilipid layer. This experiment also suggests that the Magic Sand effect depends on surface tension. We have found that the "Magic" effect disappears for solvents with surface tensions (γ) below about 40 dynes/cm: 50% methanol/water solutions (γ = 35) do not show the effect, while 25%

solutions ($\gamma = 46$) do; dioxane at 55% ($\gamma = 39$) shows a slight effect; ethylene glycol ($\gamma = 48$) and glycerol ($\gamma = 63$) do, while acetophenone ($\gamma = 39$) does not. Thus the Magic Sand effect calls for a different explanation than the hydrophobic effect, and the model should not be confused with that which it models!

Free Energy/Entropy:

If oil dissolved in water, the increasing number of water molecules which surround the smaller droplets would be more constrained to certain configurations than they are in pure water. This leads to a decrease in entropy, which makes the process non-spontaneous in spite of its exothermicity[11]. The "iceberg" model of hydrophobicity makes analogy to crystalline hydrates of hydrocarbons which form ice-like clathrates at temperatures up to 68^{o}F. The hydrophobic effect may be defined in terms of its thermodynamics, specifically characteristic temperatures T_H (~25^{o}C) where ΔH^{o}, the transfer enthalpy, is zero, and T_S (~113^{o}C) where the transfer entropy is zero[12]. These result from a strong temperature dependence of the enthalpy and entropy (a large change in heat capacity on salvation), so that around room temperature the disaffinity of oil for water is mostly entropic, while in hot water, the disaffinity of oil for water is mainly enthalpic. The Magic Sand effect provides concrete imagery to which these difficult concepts may be related, and it provides motivation to learn the thermodynamics.

Reverse-Phase HPLC: If a 1.2 x 15 cm test tube is coated with silicon grease or Vaseline®, then Magic Sand is applied Sand to coat the outside, and then thrust through Magic Sand (preferably of a second color) floating on water, the floating Magic Sand "adheres" to the Magic Sand on the tube.

This is not a perfect model: If sea sand is used in place of the Magic Sand on the test tube, Magic Sand still adheres to it to some extent. If the sea sand is wetted first, Magic Sand has little tendency to adhere. Adherence to the dry sea sand must be physical, with the graininess of the sand dragging the Magic Sand under the surface, where the hydrophobic effect pushes it as a sheet against the sea sand.

Biogenesis: At an early stage in the development of life, RNA molecules and the proteins whose synthesis they direct must have achieved advantage by natural selection, most likely by being segregated in "protocells"[13], allowing living things to evolve. The aqueous environment was critical in the formation of structures capable of acting as cell membranes, and Magic Sand illustrates the spontaneous organization of interesting structures. Without water and the hydrophobic effect, cell structure may not have evolved, so as Tom Robbins says[14], "Human Beings were invented by water as a device for transporting itself from one place to another." Magic Sand is not a perfect model for the bilayer membranes of cells, which are made of amphiphiles, rather than completely hydrophobic substances. In "Mayonnaise and the Origins of Life"[15], Herbert Morowitz speculated on this process.

Guide to Preparing and Presenting the Demonstration

The most basic demonstration is simple: Just slowly pour ~100-200 mL of dry Magic Sand into ~400 mL of water in a ~600 mL beaker. Observe the "rabbit gut"-like shapes. Decant the water slowly, and observe the (now dry and shapeless) as you continue to pour the Magic Sand into another 600 mL beaker. Repeat with sea sand and observe wetting by water.

Repeat Magic Sand demonstration with a less polar liquid, like ethanol or other alcohols, salad oil, detergent mixtures, hexanes, and so forth.

Safety and Disposal Issues:

Magic sand is not toxic. It is reusable, and large amounts of the dry sand should not be drain-disposed (you would not drain dispose large amounts of any insoluble solid!). Liquid should be decanted from the sand as much as possible, and the remaining sand and liquid poured onto a nest of paper towels to absorb the residual liquid. After the towels dry, they can be folded into a trough to help guide the dry sand into a storage container.

How the Demonstration is used in the Classroom

Most students have not seen Magic Sand, and are surprised by its behavior, so these demonstrations are very good motivators for learning about the structure of water, its behavior as a "universal solvent", and the fact that its behavior as a non-solvent can be even more important, leading to the formation of membranes through the hydrophobic effect. Displaying the "rabbit gut" forms that Magic Sand displays in water is a natural attention-getter, and if it is related to biogenesis, it can be a strongly motivating force for learning about the polarity of water and how it results from its molecular structure. Because the surface of Magic Sand is coated with a nonpolar substance[16], it behaves like a hydrocarbon or nonpolar gas, the classic hydrophobic substances.

This behavior may be contrasted with what is observed when sea sand is poured into water. The Si-OH groups on the surface form hydrogen bonds to water, so the sand is "wetted"[4].

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