Good Practice Report

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A billion times smaller than us: helping students comprehend the molecular scale

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Abstract: Comprehension of molecular scale is an essential component of a chemistry student's education. However, it is especially difficult for most to wrap their heads around just how small the nanometer scale is at which the molecules they are taught about exist. Using 3D printing techniques to aid in visualization, we can model spherical molecules, namely buckminsterfullerene (C_{60}) and the cuboctahedral gold cluster Au_{55}, and scale them up by eight orders of magnitude. The new size of these molecules is comparable to a globe 13 cm in diameter, a model of the Earth scaled down by eight orders of magnitude. Seeing and holding both of these objects resized to similar dimensions, students are able to get a sense of how the molecular scale compares to the handheld scale. The fact that the molecule is scaled up by a factor of 10^{24} in volume also nicely contextualizes the magnitude of Avogadro's number ($\sim 0.6 \times 10^{24}$), the constant of proportionality that converts the molecular scale to the handheld scale.

Keywords: chemical education research; first-year undergraduate/general; hands-on learning/manipulatives; high school/introductory chemistry.

Introduction

Students learn that molecules are about a nanometer in size. It is clear, however, that imagining something that small – nine orders of magnitude, or a billion times smaller than us – is difficult. Comprehending scale (scale literacy) (Gerlach et al., 2014; Murphy, 2019; Trate et al., 2019b) is an essential theme in the instruction of science and chemistry in particular (Trate et al., 2019a). Several different studies into the ability of students to conceptualize scale differences have appeared, and Tretter et al. (2006) in their discussion of mental maneuverings across many orders of spatial magnitude, write: "…to effectively engage at very large or small scales, it is necessary to mentally transport oneself to a new world at that scale. Is it important to connect that other-scale world to the human-scale one? From comments made by experts, it seems that at least a tenuous link must be maintained to process and connect this knowledge to the rest of their experiences. Attempts to make this connection are difficult, but to conceptualize these other-scale worlds as completely independent of how they relate to everyday human existence would likely make any such mental exercises less useful."

As such, efforts to help ground the concept of scale are useful contributors to student understanding. Various efforts have been made to help students with this task. For example, there are interactive zooming visualizations available in numerous locations online (Carykh, 2012; Davidson, 2017; Genetic Science Learning Center, 2020; Huang & Martori, n.d.; Nikon, 2021), which allow users to move from molecular to galactic scales in logarithmic leaps. We wanted to provide students with a physical means of imagining the vast differences in scale between us and a molecule, using a scale model of the Earth (an object familiar to all students, in the form

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of a globe) and a 3D-printed scale model of a molecule (3D prints have proven to be useful aids to visualization in other chemistry contexts) (Griffith et al., 2016; Higman et al., 2017; Niece, 2019; Van Wieren, 2017). Comprehension of visual models is essential for student success in chemistry courses (Dickmann et al., 2019).

The Sun, nine orders of magnitude larger than us, is something so incomprehensibly large that most cannot wrap their heads around it. Without a way to anchor a number to an everyday concept, people struggle both with very large numbers and with very small ones (Randall Munroe's popular science book "What If?" is aimed squarely at this problem) (Munroe, 2014). If we scale up a molecule by a billion times, and scale the sun down by a billion times, we get objects that are both close to human-size (Figure 1).

Figure 1 is difficult to wrap your head around – it is hard to imagine even the size of the Earth in relation to the sun (109 Earths fit across a solar diameter, so the Earth, two orders of magnitude smaller than the sun, is represented by the 13 mm marble held by the person in the figure). It's easier for humans to imagine the scale of the Earth than the sun, as most of us can comprehend the size of the globe if we've been in a plane and traveled any substantial distance and/or observed the curvature of the globe from up high. This paper describes a handheld demonstration that conveniently allows the size of a molecule to be compared to the size of the Earth. It is a teaching analogy (Glynn, 1994) that says, "you are to a molecule as the Earth is to you".

For a molecule that is similarly shaped to the Earth, and 10^{16} times smaller in all dimensions, we offer two suggestions. Buckminsterfullerene, C_{60}, is both a famous molecule and one that is approximately spherical (it is a truncated icosahedron). Scaling up C_{60} by exactly eight orders of magnitude generates a model of the molecule 80 mm (3 ⅛") in diameter, a scale that can be 3D printed inexpensively. A suitable example can be found in the supporting information as generated by the excellent 3D printing option available on the freely available Mercury program (The Cambridge Crystallographic Data Centre, n.d.; McIndoe, n.d.; Wood et al., 2017). Any molecule can be printed on the same scale ($10^8 \times$ bigger) using Mercury's default setting for 3D printing, which is 1 Å = 10^{-10} m = 10 mm. A slightly less spherical, but closer in size option for the model: the gold cluster Au_{55}, a cuboctahedral 3-shell nanoparticle with a cubic-close packed arrangement of atoms (i.e., a small, near-spherical fragment of a metal lattice) (Schmid, 2008). It features a central gold atom surrounded by 12 gold atoms, itself surrounded by a third layer of 42 gold surface atoms.

Scaling the Earth (12,742 km in diameter) down by exactly eight orders of magnitude requires a globe approximately 13 cm (5") in diameter, easily sourced online (search any large retailer for "5-inch globe") (Figure 2, depicted with 3D printed models of Au_{55} and C_{60}).

The demonstration is straightforward; the globe is presented to the class and it is discussed how the size of the Earth is comprehensible to the students (maybe they have seen the curvature of the Earth from a high vantage point, or traveled a significant distance around the planet). The scale difference is revealed as being

Figure 1: Sun at 10^{-9} scale (1.4 m, background), person (1.6 m, right), fullerene at 10^9 scale (0.7 m, left). The person is holding an Earth-scale object also at 10^{-9} scale (a 13 mm stainless steel ball-bearing). Sun image from https://solarsystem.nasa.gov/solar-system/sun/overview/.

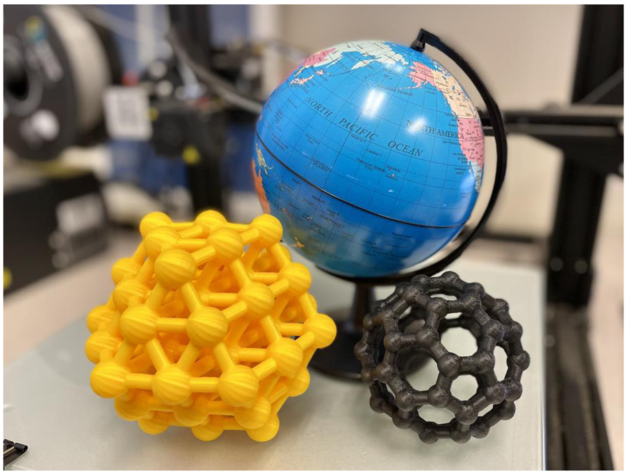

Figure 2: 3D printed models of Au_{55} (yellow) and C_{60} (black) scaled up by 10^8, next to a 13 cm (5") globe.

10^{-8}, and the students are informally polled on how big they think a molecule would be if it was scaled UP by 10^8 times. Brief discussion should be encouraged (between students first, then with the instructor), and the answer revealed. The demonstration is most powerful if you allow students to lay their hands on the two objects by passing them around the class. Further explanation should reiterate that both objects are eight orders of magnitude out of scale: the globe is one hundred millionth of Earth's actual diameter, and the 3D print is one hundred million times the diameter than the molecule it is based on. The volumes are different by 10^{24}, which is close to Avogadro's number ($6.02214076 \times 10^{23}$), the constant of proportionality that defines the number of particles in a mole of a substance. This similarity is not of course a coincidence, rather that scaling something up by Avogadro's number brings an object from the molecular regime to the handheld scale, and this demonstration strives to help students perform that piece of mental gymnastics.

We surveyed student recollection of this demonstration seven months after they encountered it in the first lecture of their first class of university chemistry. 900 students were invited to partticipate (the entirety of the first year class in 2021), and 62 (7%) responded. Given the elapsed time and their full program of courses in the intervening period, their memory of the demonstration was hazy; the majority of students were not sure or could only vaguely remember the demonstration, and 45% reported they could not remember it at all. Perhaps unsurprisingly given those results, few could recall the factor by which the diameter of the molecule had been scaled up, with only 14% picking the correct factor, and most overestimating the answer as a billion (35%) or a trillion times (39%). They did somewhat better in answering "In volume, the globe differs in size to the Earth by a magnitude approximately equal to which constant?" as being Avogadro's number (37%, a plurality). While these results are unremarkable, it is probably true that their recollection of any single minute (the length of time taken for this demonstration) of their lectures from two semesters ago are likely to be similarly fuzzy. We consider the demonstration well worth the short time devoted to it in class, even if explicit student recollection is limited, but the survey has certainly indicated that revisiting the analogy later in the course is important if the lesson is to have a lasting impact.

Conclusions

Students can be helped in grasping the molecular scale by introducing them to 3D printed molecular models (Au_{55} and/or C_{60}) that have been scaled up by eight orders of magnitude, and comparing their size to a small globe that has been scaled down by eight orders of magnitude. The similarity in size between these objects paints an instantly comprehensible picture of what eight orders of magnitude of size difference really means, and helps students understand why Avogadro's number is the size it is.

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Supplementary Information

STL files of C_{60} and Au_{55} for 3D printing. Survey results.

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