International Journal of Engineering Education Vol. 28, No. 5, pp. 1088–1094, 2012
Printed in Great Britain

0949-149X/91 $3.00+0.00

Pop Culture: A Soap Bubble-based Framework for Nanoeducation Outreach*

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Lecture demonstrations can be a significant aid to learning, when coupled with appropriate teaching methods and conceptual knowledge. However, in-class experimental demonstrations of core concepts in nanotechnology, such as self-assembly of molecular systems, is exceptionally challenging under poorly controlled classroom conditions. In this work, I demonstrate the use of soap bubbles as easily visualized, accessible and relatively robust examples of molecular systems, that are already familiar to students, yet can be used to illustrate complex principles of self-assembly. Utilizing dynamic soap bubble sculptures, this work illustrates a simplified framework within which to teach molecular self-assembly in nanoeducation outreach programs at the secondary school level. Student learning and interest in nanoscience was assessed via an ad hoc survey to determine the suitability and effectiveness of soap bubbles as learning tools for this target audience. The results demonstrate that even academically strong students at the secondary level had largely not considered the link between molecules and soap bubbles, but described a high level of intrinsic interest in the subject material. Self-assessed levels of concept comprehension were high, and students described an increased interest in pursuing studies in the physical sciences and specifically within nanotechnology.

Keywords: bubbles; soap; sculptures; self-assembly; molecular; demonstration; lecture; experiment; classroom; education; nanotechnology

1. Introduction

The projected need for scientists and engineers working at the nanoscale [1, 2], in combination with perceived declines in science literacy and interest worldwide [3] has prompted the development of nanoscience-based education modules designed to spark interest in the physical sciences [4] and train the next generation of nanotechnologists. Education and outreach activities at the pre-undergraduate level are crucial first steps in encouraging students to pursue nano-related studies, for several reasons. First, current generations of students are increasingly exposed to nanoscience advances through the media, but are not provided with a systematic framework to understand this approach to engineering [5]. The feeling that a subject is far beyond comprehension can significantly discourage pursuit of such fields of study. Second, nanoeducation provides a framework to integrate traditionally separate physical sciences, as disciplines are barely distinguishable at the molecular level [4]. Studies have demonstrated that 'breadth-first' interdisciplinary approaches can help students appreciate the relevance of science outside the classroom [6, 7]. Third, as nanoscience is perceived as having great potential to improve the human condition, pre-undergraduate educational modules will likely be viewed as important and practically useful, encouraging a positive attitude towards science in general [8]. Finally, because the phenomena, properties and dominant forces at the nanoscale are so different from the macroscale, students will be forced to rethink their preconceptions about how the world works, leading to the development of better thinking and problem solving skills [4].

Though some excellent resources exist with which to teach such subjects [7, 9–11], bringing core nanoscale phenomena into the classroom remains challenging. Incorporating interactive and physical lecture demonstrations has been well-established to improve student learning and retention [12–15], but the complexities associated with conducting robust and real-time demonstrations of self-assembling molecular systems makes this a difficult strategy to enact. Though computer simulations and macroscale analogs could arguably be used to demonstrate such phenomena [16, 17], such approaches rarely leverage student's prior knowledge of the subject, a factor clearly shown to improve student learning and retention [18]. Moreover, few experimental demonstrations have been designed to present a broader systematic approach or conceptual framework for nanoscience and engineering.

In this work, I demonstrate the use of soap bubbles to provide an in-class experience of molecular interactions and emergence in complex systems. Soap bubbles have previously been suggested as classroom demonstrations of various mathematical and scientific phenomena, including topography, density, interference colours, static electricity and even as a representation of galactic structures,

* Accepted 1 June 2012.

in which galaxies exist on the 'wall' of a large, expanding void [19]. Bubbles are well-suited for classroom demonstrations, as most students have some prior knowledge and experience in playing with them, and the scale of the structure can be easily observed via visible light wave interference patterns. Here, inspired by vaudeville soap bubble artists [20], I utilize soap bubble 'tricks' and sculptures to develop and illustrate an easily accessible, simplified framework to discuss molecular self-assembly. By revisiting a physical system familiar to most students, and reconstructing that system in unexpected and often delightful ways, I provide an accessible, 'real' example of molecules interacting synergistically to produce emergent behaviour, and suggest that such an approach can lead to increased interest in pursuing nano-related studies.

2. Materials

Tools to blow soap bubbles are easily accessible in most parts of the world. In the described demonstrations, I make use of commercially available circular plastic bubble wands, plastic straws, and some containers to hold the bubble solutions. Bubble solutions can be more complicated, and the effectiveness of each formulation is known to be dependent on humidity, temperature and dust particle count. In most cases, being indoors can address these issues, and liberal use of a water spray bottle before bubble demonstrations significantly reduces dust particles in the air. Commercial bubble solution concentrate was purchased (Bangwool Land Co., Ltd.; Korea), and diluted as directed by the manufacturers. Other commercial alternatives are reported to work just as well, and recipes for home-brewed solutions are readily available on the internet. In order to make certain bubbles clearly visible in a classroom, a device to fill the bubbles with fog was built. The 'Wizard Stick' (Zero Toys; Concord, MA, USA) is a hand-held, battery-operated propylene glycol-based device that produces fog on demand. The fog can be stored in a chamber fitted around the toy nozzle. A pair of straws connected to the chamber can then be used to blow a fog-filled bubble.

3. Methods: lecture outline and framework

The simplified framework for molecular self-assembly that can be extracted from soap bubble demonstrations is based upon the following three key points:

(i) Systems are stable at energy minima
(ii) Multiple stable local minima exist
(iii) Interactions or external forces can drive system energy towards distinct local minima.

These key points are broadly applicable to any self-assembling system, and leads towards a discussion and understanding of how synergistic interactions between different molecular species results in emergent complex behaviour of a system; a discussion which can then be extended to any self-assembling system. Soap bubbles provide a simple molecular system demonstrating each of these key features.

After drawing attention to the iridescent colour patterns on soap bubble films, a brief discussion and explanation concludes that the films range in thickness from 4 nanometers to 100s of nanometers, as evidenced by observed constructive and destructive interference of light [21].

Once soap bubbles are identified as nanostructured children's toys, fog-filled bubbles are popped (Fig. 1) to demonstrate that the film is under mechanical tension. When the bubbles are popped via the wand opening (Fig. 1C, D), the soap bubble contracts to force the fog out of the bubble, forming a plume of fog. The link between the tension in the film and the shape of the bubble is then drawn: when the bubble film is under tension, the spherical shape is the smallest amount of material (and hence, the smallest amount of energy) required to encapsulate a given volume at a slightly elevated pressure inside the bubble. Thus, systems are stable at energy minima (point (i)). While this is intuitively simple for a sphere, determining structures that minimize materials usage given other constraints can be quite challenging, and are known as Plateau problems. These are introduced by framing the problems as highway-planning challenges [22]. Given a number of cities (or nodes) in specified locations, how may they all be connected using the least amount of road? Minimal material structures for three and four regular spaced nodes are shown in Fig. 2A and B, and the triple point structure (120° angles) frequently observed in nature (turtle shells and mud cracks, for example) is then explained as a key feature of geometric minimization in two dimensions. Soap films can then be used to demonstrate the formation of these triple points, by placing pegs between two Plexiglass plates to represent the nodes, and dipping the resulting sandwich structure into soap solution [23]. The resulting film structure settles into a minimal energy state, reproducing the triple point junctions. However, the non-uniform arrangement of nodes demonstrated in Fig. 2C demonstrates that not all energy minima are equal. Both structures in Fig. 2C (and all three structures in Fig. 2D) can be achieved by soap films, depending on the angle and rotation with which the sandwich plate is removed from the solution. Thus, multiple stable local minima can exist (point (ii)). Furthermore, blowing on the bubble films can cause the structures to reform in

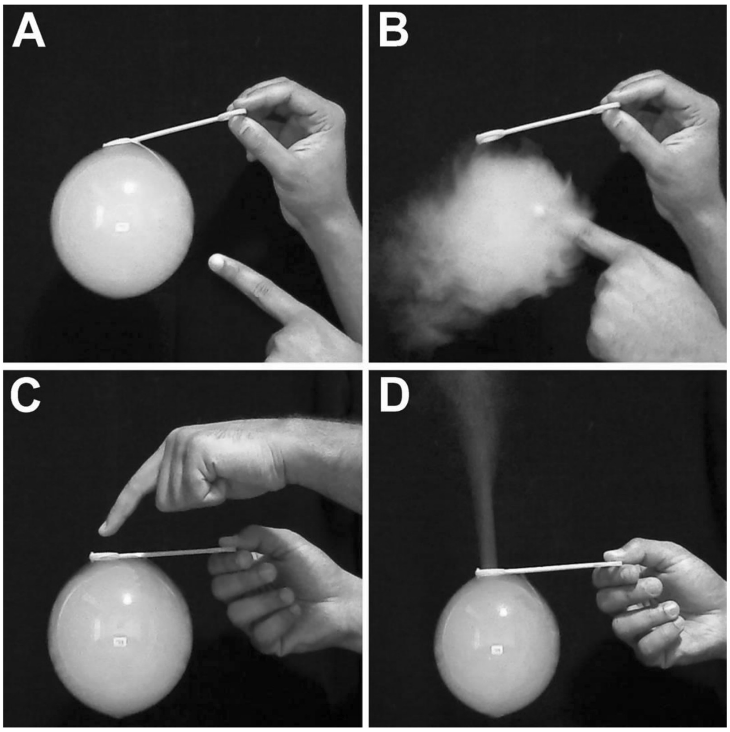

Fig. 1. Soap bubble films are under continuous tension. A fog-filled soap bubble is popped from (A, B) the side, and (C, D) the top, to demonstrate that tension in the film creates a driving pressure, forcing the fog through the bubble wand ring.

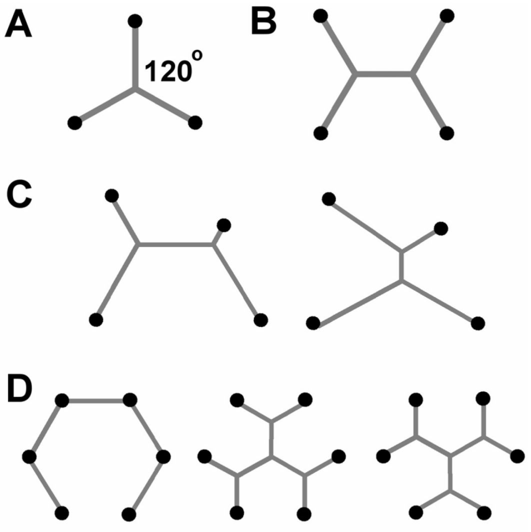

Fig. 2. Plateau problems determine minimal material solutions in connecting nodes spaced in varying configurations. (A) A triple junction most efficiently connects three equidistant nodes, while (B) a pair of triple junctions best connects nodes placed in a square pattern. (C) Four irregularly spaced nodes have non-equal minimal material solutions, despite both using triple point structures. (D) Six regularly spaced nodes have three distinct solutions, each of which utilizes equivalent amounts of material.

another stable state, demonstrating that external forces can be applied to change local minima (point (iii)).

To reinforce these key conceptual points, a predict/observe/explain teaching sequence [24] is then used for more complex bubble demonstrations. Energy minimization is demonstrated beyond two-dimensional structures by constructing a caterpillar bubble (Fig 3A). The angles between the planar interface and the bubble walls form triple point junctions, which would not occur in unstable structures (Fig 3B). Tetrahedral angles, the three-dimensional analog for two-dimensional triple junctions (Fig 3C) are then introduced via the bubble cube (Fig 3D), a bubble blown within six connected bubbles of equal size. More complex structures such as those in Fig. 3E can also be demonstrated, and many of these structures can be replicated by dipping wireframe models into bubble solutions [19].

Finally, the dynamic building and collapse of a soap bubble structure (Fig. 4) is used to demonstrate the existence of multiple local energy minima and the ability to transition between them within the same system. Two distinct soap bubbles are connected (Fig 4A–C) by driving them against each other (Fig 4B). The resulting stable bubble pair (Fig 4C, D) is then disrupted by sliding a wet straw into the bubble and disrupting the interface by applying a brief suction (Fig 4E). The bubble collapses into the lowest stable energy state (Fig 4F), thereby demonstrating how externally applied forces can drive systems out of their local energy minima and into a different minimal energy configuration.

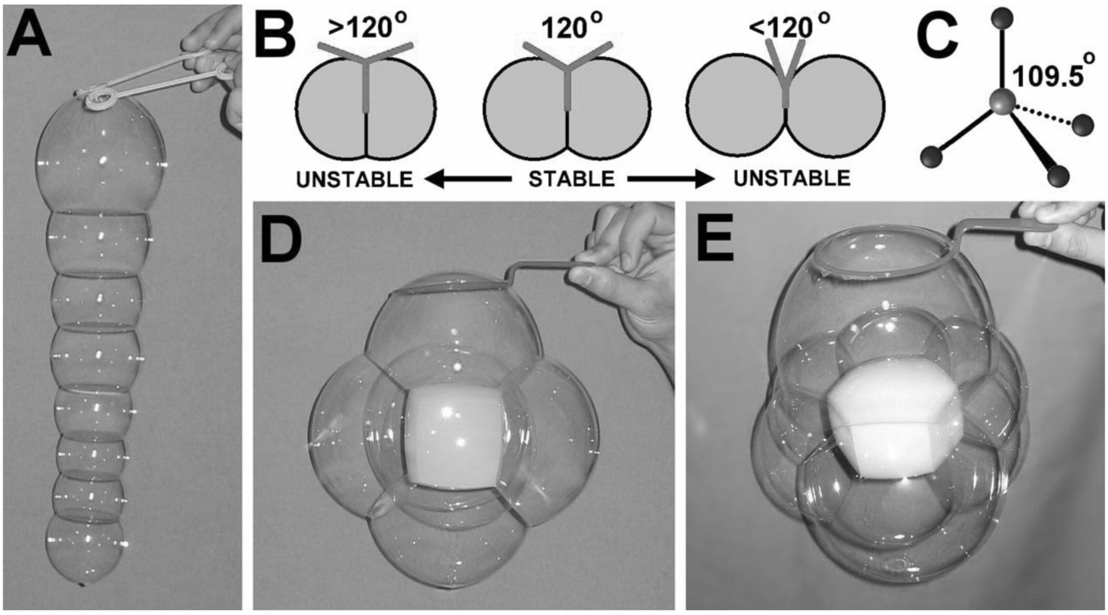

Fig. 3. Demonstrating the connection between energy / material minimization between two-dimensional and three-dimensional structures. (A) A soap bubble caterpillar structure consists of (B) triple points between the flat surface between bubbles and the bubble walls. More material is used when the spacing's between the bubbles dictates an angle greater or less than 120°. In three-dimensional interactions, a (C) tetrahedral angle represents the geometric structure of minimal energy, demonstrated with (D) a bubble cube or (E) a more complex polygon.

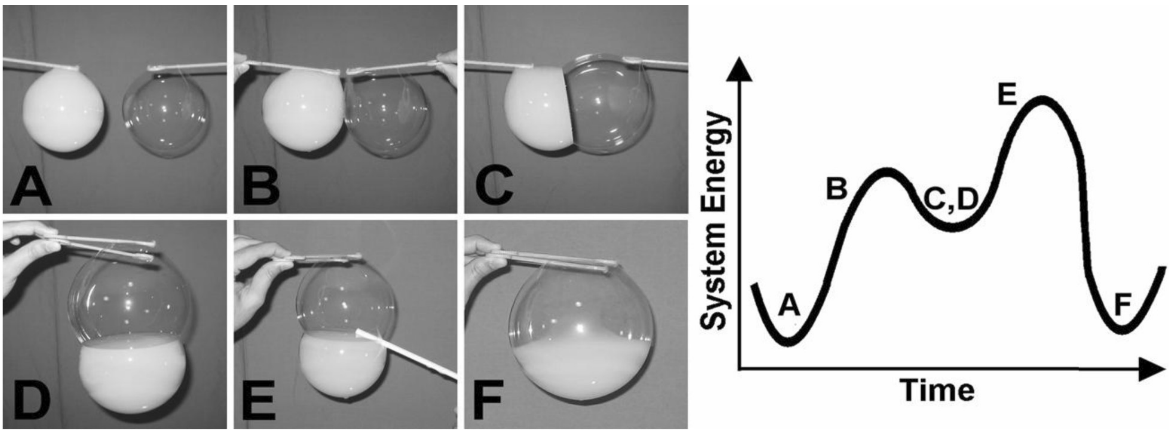

Fig. 4. A soap bubble system is used to demonstrate how stable states exist within local energy minima, and that the system can settle in alternative states when these stable states are disrupted. (A) A clear and fog-filled bubble are (B) provided sufficient kinetic energy to (C, D) merge, forming a stable system. Mechanical energy is then introduced by (E) inserting a straw and disrupting the interface. (F) The system then collapses to the next lowest stable energy state, evidenced by the combined contents of the two bubbles.

The lecture is completed with an explanation and analysis of how the interactions between soap molecules and water molecules create stable equilibrium structures, and concludes by using the developed framework to discuss examples of current natural and engineered self-assembled structures, such as in biological cells and in the development of organisms. Throughout the lecture, the interdisciplinary nature of nanotechnology is made clear through the use of supporting examples, thereby drawing connections between materials science, biology, mathematics, physics, and chemistry.

4. Methods: Assessment of learning

This lecture has been delivered to approximately 400 students attending the Shad Valley program (http://www.shad.ca) at Queen's University and the University of Waterloo over 5 years. Shad Valley is a four-week Canadian summer enrichment program, in which approximately 500 students in grades 10–12 are selected from an international pool of applicants to spend a month at one of ten host university campuses across the country. Applicants are selected based on academic and extracurricular excellence, demonstrated creativity and leadership potential. At each host campus, the 'Shads' are immersed in a university level learning community, and exposed to a variety of subjects. This lecture has formed a part of the engineering and science curriculum at the Queen's and Waterloo campuses, and feedback was solicited from the 48 students attending the Shad Valley Waterloo 2011 program. In the absence of a validated measure to specifically assess learning of principles underlying molecular self-assembly, feedback for this pilot study was solicited via an anonymous, ad hoc survey questionnaire. A 7-point Likert scale was selected to assess (1) suitability of the lecture content for the target audience, (2) appreciation of the underlying principles of the subject, and (3) interest generated in nanotechnology and the physical sciences.

5. Results and discussion

The survey results (Fig. 5) and comments collected reveal that despite students' previous childhood experiences with soap bubbles, less than 17% had previously considered the link between soap bubbles and molecules. Despite this relatively low level of prior knowledge and consideration, 98% of the group agreed that the lecture material was intrinsically interesting, with 75% strongly agreeing with this statement. Comments suggested that the sense of wonder found in observing familiar systems behave in extraordinary fashions, led to this intrinsic interest. These results demonstrate that the audience, despite being academically strong in the Canadian secondary education system, still had something to learn from the demonstrations.

Determining the effectiveness of the soap bubble demonstration in teaching the specific concept of 'self-assembly' is quite challenging, as the student class size is not permissive to creating control groups who have been taught the concepts without demonstrations. Furthermore, the Shad Valley philosophy is for students to set their own standards of learning, and hence no exams or tests are administered. This is advantageous in building a scholarly community and encouraging life-long learning, but requires instructors to resort to alternative assessment methods to determine if student learning has occurred. Based on informal discussions during and after class, and the quality of questions received, it became quite clear that students had a better grasp of the core concepts being taught.

Although validated measurements to assess student learning exist, these measurements have not been tested for validity and reliability in the field of nanoscience education. Since the primary purpose of this work is to demonstrate an approach to provide accessible demonstrations of molecular

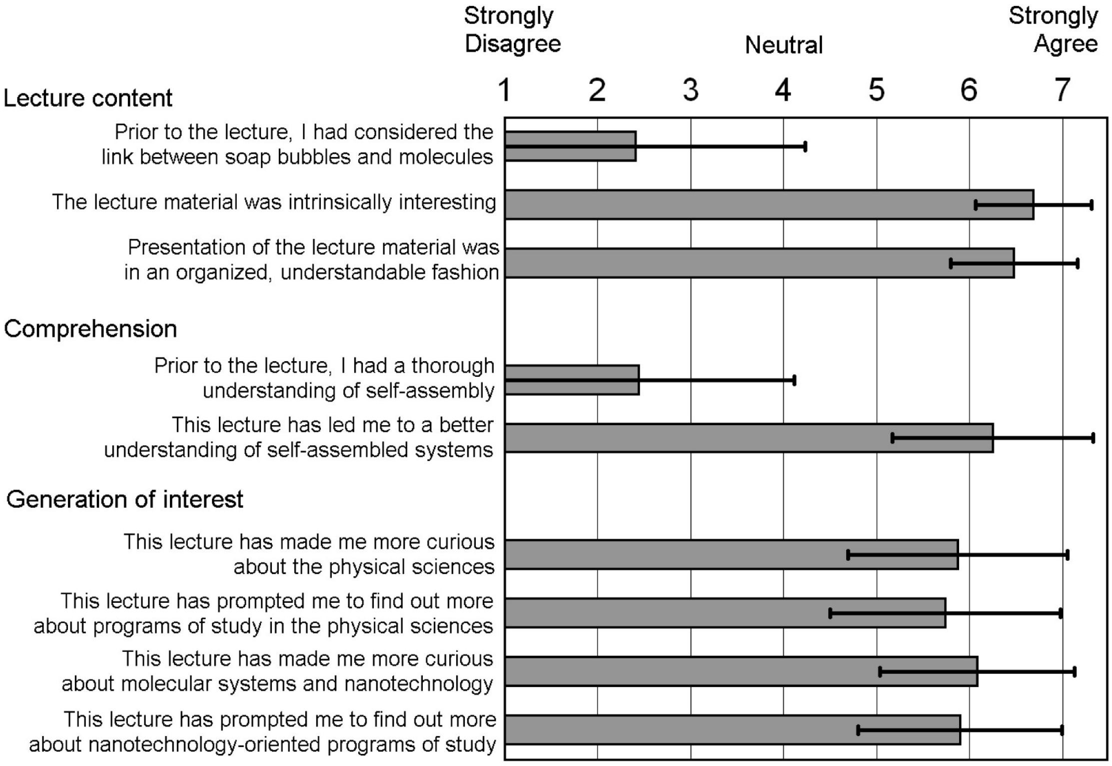

Fig. 5. Summary of student feedback collected from a voluntary and anonymous post-class survey. Error bars represent means ± standard deviations for 48 student responses per statement.

self-assembly in the classroom, and not to accurately and reliably assess student learning of the material, a simple ad hoc survey was used to formalize anecdotal evidence of student learning. This approach is limited in that it has not been assessed for reliability or validity, and hence cannot be generalized. While future work in this area will require rigorous, reliable and validated measures of student learning, the results of this small-scale pilot assessment demonstrates the potential of this lecture material in the classroom.

The ad hoc survey indicates that less than 15% of the class agreed that they had a thorough understanding of self-assembly prior to the lecture, while 94% agreed that observing soap bubbles has led them to a better understanding of self-assembled systems, demonstrating significant learning. Further studies are required to determine degree of comprehension, as well as the effectiveness of the demonstrations over traditional techniques.

To determine whether this outreach activity provided increased interest in considering a nano-related field, survey questions were designed to gauge how observing soap bubble phenomena increased curiosity about the physical sciences, and specifically molecular and nanotechnology systems, and whether this lecture has prompted students to find out more about future programs of study in these areas. Between 85 and 95% of respondents expressed increased interest in both the physical sciences and in nanotechnology and molecular systems as future areas of study, as a result of the bubble demonstrations and lecture. Although the questionnaire was designed to be clearly specific to the bubble demonstrations, it must be acknowledged that this will not eliminate any potential bias introduced during the Shad Valley application screening process, which may select for students predisposed towards Science, Technology, Engineering and Mathematics (STEM)-related fields. However, survey comments indicated that the broadly applicable framework unifying different disciplines of study was a strongly appealing approach through which to continue further studies, suggesting that the lecture and demonstrations did generate additional interest in pursuing STEM-related studies.

In addition to pre-college students, this soap bubble demonstration has also been delivered to junior and sophomore undergraduates from various universities at the Undergraduate Nanotechnology Conference (held in Toronto, Canada; 8th March, 2008). Though no formal survey was conducted, informal assessment and discussion showed similar trends as to student engagement, interest and learning. A common theme repeatedly raised by students and colleagues is the sense of wonder achieved when closely revisiting a system that is supposedly familiar and commonplace, while providing a sufficiently advanced conceptual framework within which to understand it. While the effectiveness of classroom demonstrations in student learning has often been questioned [25, 26], providing clear take-away concepts and repeated opportunities for prediction and observation appears to have ameliorated these concerns.

6. Conclusions

Implementing in-class demonstrations of core concepts in nanotechnology such as self-assembly of molecular systems is challenging due to the lack of a robust experimental system that is simple enough to understand at the pre-undergraduate level, yet complex enough to demonstrate important underlying principles. Soap bubbles provide an easily accessible demonstration familiar to most students, yet able to illustrate surprisingly complex behaviours. Demonstrating a simplified framework for self-assembly of molecular systems via soap bubble ‘tricks’ was shown to be a promising approach in bringing nanotechnology into the classroom, to generate interest and an improved understanding of nanoscience and technology.

Acknowledgements—I gratefully acknowledge the Shad Valley program (http://www.shad.ca), for the opportunity and financial support to develop and disseminate the described teaching and learning experience. I also thank Mr. Keith Johnson for helpful advice, and Mr. Tom Noddy, who inspired my interest in these systems decades ago.

References

1. M. C. Roco and W. S. Bainbridge, *Societal implications of nanoscience and nanotechnology*, Springer, 2001.
2. M. C. Roco, Converging science and technology at the nanoscale: opportunities for education and training, *Nature Biotechnology*, **21**(10), 2001, pp. 1247–1249.
3. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington D.C., 2007.
4. R. P. H. Chang, A call for nanoscience education, *Nano Today*, **1**(2), 2006, pp. 6–7.
5. M. D. Cobb and J. Macoubrie, Public perceptions about nanotechnology: Risks, benefits and trust, *Journal of Nanoparticle Research*, **6**(4), 2004, pp. 395–405.
6. G. S. Aikenhead, *Science education for everyday life: evidence-based practice*, Teachers College Press, New York, NY, 2006.
7. P. Y. Furlan, Engaging Students in Early Exploration of Nanoscience Topics Using Hands-On Activities and Scanning Tunneling Microscopy, *Journal of Chemical Education*, **86**(6), 2009, p. 705.
8. J. S. Eccles and A. Wigfield, Motivational Beliefs, *Values and Goals, Annual Review of Psychology*, **53**(1), 2002, pp. 109–132.
9. G. Planinsic, A. Lindell and M. Remskar, Themes of nanoscience for the introductory physics course, *European Journal of Physics*, **30**(4), 2009, pp. S17–S31.
10. A. Greenberg, Integrating Nanoscience into the Classroom: Perspectives on Nanoscience Education Projects, *ACS Nano*, **3**(4), 2009, pp. 762–769.

11. B. Hingant and V. Albe, Nanosciences and nanotechnologies learning and teaching in secondary education: a review of literature, *Studies in Science Education*, **46**(2), 2010, pp. 121–152.
12. G. Ashkenazi and G. C. Weaver, Using lecture demonstrations to promote the refinement of concepts: the case of teaching solvent miscibility, *Chemistry Education Research and Practice*, **8**(2), 2007, pp. 186–196.
13. M. D. Sharma, I. D. Johnston, H. Johnston, K. Varvell, G. Robertson, A. Hopkins, C. Stewart, I. Cooper and R. Thornton, Use of interactive lecture demonstrations: A ten year study, *Phys. Rev. ST Phys. Educ. Res.*, **6**(2), 2010, p. 020119.
14. D. R. Sokoloff and R. K. Thornton, Using interactive lecture demonstrations to create an active learning environment, *The Physics Teacher*, **35**(6), 1997, p. 340.
15. R. Zimrot and G. Ashkenazi, Interactive lecture demonstrations: a tool for exploring and enhancing conceptual change, *Chemistry Education Research and Practice*, **8**(2), 2007, pp. 197–211.
16. K. C. Trundle and R. L. Bell, The use of a computer simulation to promote conceptual change: A quasi-experimental study, *Computers & Education*, **54**(4), 2010, pp. 1078–1088.
17. N. Rutten, W. R. van Joolingen and J. T. van der Veen, The learning effects of computer simulations in science education, *Computers & Education*, **58**(1), 2012, pp. 136–153.
18. D. A. Bergin, Influences on classroom interest, *Educational Psychologist*, **34**(2), 1999, pp. 87–98.
19. E. Korenic, Let Them Blow Bubbles, *Science Teacher*, **55**(5), 1988, pp. 44–47.
20. T. Noddy, *Tom Noddy's bubble magic*, Running Press, Philadelphia, PA, 1988.
21. C. V. Boys, *Soap bubbles and the forces which mould them*, Dover Publications, Mineola, NY, 1959.
22. C. Isenberg, *The science of soap films and soap bubbles*, Dover Publications, Mineola, NY, 1978.
23. P. Stevens, *Patterns in nature*, Little Brown, Boston, MA, 1974.
24. L. E. Klopfer, A. B. Champagne and R. F. Gunstone, Naive Knowledge and Science Learning, *Research in Science & Technological Education*, **1**(2), 1983, pp. 173–183.
25. M. Baddock and R. Bucat, Effectiveness of a Classroom Chemistry Demonstration using the Cognitive Conflict Strategy, *International Journal of Science Education*, **30**(8), 2008, pp. 1115–1128.
26. C. Crouch, A. P. Fagen, J. P. Callan and E. Mazur, Classroom demonstrations: Learning tools or entertainment?, *American Journal of Physics*, **72**(6), 2004, p. 835.

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