IBI* SERIES WINNER

Discovering Nanoscience

Exploring Gold Nanoparticles, the IBI Prize–winning module, guides students' construction and evidence-based refinement of their personal models of gold nanoparticles.

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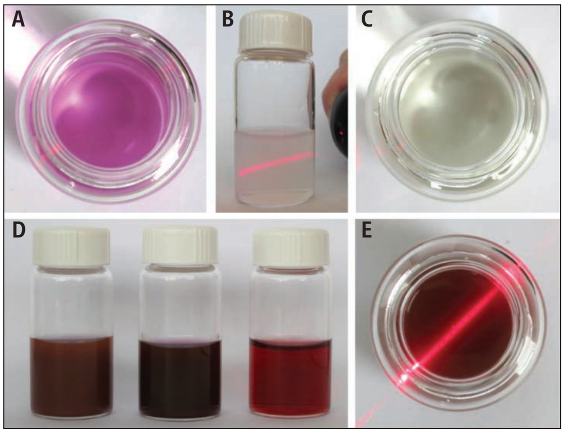
The President's Council of Advisors on Science and Technology stresses the importance of adoption of empirically validated instructional practices, such as inquiry-based laboratory experiences, in higher education (*1*). The Exploring Gold Nanoparticles laboratory module employs an inquiry-based instructional tool called the Model-Observe-Reflect-Explain (MORE) Thinking Frame (*2*) to support student construction of evidence-based models of nanoparticles in introductory chemistry courses. Using MORE has been shown to enhance students' understanding of the nature of science and of scientific models compared with traditional teaching methods (*3*, *4*).



Nanoparticles revealed. Using laser pointers, students explore various mixtures, collecting evidence to inform their models. A laser shines on (**A**) a $KMnO_4$ (aqueous) solution, (**B**) a fine suspension of AgCl in water, and (**C**) a $HAuCl_4$ (aqueous) solution. (**D**) The three gold nanoparticle mixtures that students synthesize. (**E**) A laser shines on one of the gold nanoparticle mixtures. When probed with the laser, scattering is not observed in the solutions (A) and (C), but is observed in the colloidal mixtures (B) and (E).

The MORE Thinking Frame scaffolds students' thinking as they work to construct and evaluate evidence-based, molecular and/or nano-level models of chemical systems. A MORE module begins with a written, prelaboratory assignment (*5*) that prompts each student to describe his or her ideas about the system under study from macroscopic and molecular-level perspectives. This serves as the student's initial model. In writing their models, students are encouraged to reflect upon and articulate their own ideas, rather than to look up scientists' ideas. Next students conduct experiments in the laboratory (observe) and are explicitly prompted to reflect upon the implications of their observations as they relate to their initial model ideas. Students then refine their models and explain how their revised molecular-level ideas are consistent with the experimental evidence they collected.

After completing an iteration of MORE, students apply MORE to a subsequent set of laboratory activities, which provides additional opportunities for them to refine their models. Each student presents a refined model, explains why it has (or has not) changed from his or her previous model, and proposes a generalized model that could be used to understand new situations. At the end of a module, each student proposes a next experiment that would help further refine or test his or her molecular-level model.

Although the MORE Thinking Frame is well-suited to guide students' thinking as they conduct original research, in our general chemistry laboratory course, we have more often applied it to investigations for which there is a fundamental, scientifically accepted model that has not yet been presented to students. Research has shown that instructional paradigms in which students first work to develop general rules or models, and expert ideas are presented only after students complete their investigations, promote deep understandings that facilitate transfer of learning [e.g., (*6*)]. Research in the context of another MORE module (*7*) indicates that student engagement in three thinking processes is strongly correlated with subsequent successful reasoning in new contexts. These include (i) constructing molecular-level models that are consistent with experimental evidence, (ii) reflecting accurately and completely on how one's own molecular-level ideas changed relative to previous ideas, and (iii) identifying evidence to justify model refinements as part of the reflection on how and why ideas changed.

Exploring Gold Nanoparticles is a MORE module that guides students to construct and refine their own evidence-based models of the structure and properties of colloidal gold nanoparticle systems (*5*). The initial model assignment provides students with a chemical equation for the synthesis of gold nanoparticles and asks them to describe what they expect to observe and what they think will happen on the molecular level. At the beginning of the first laboratory session, a few students present their initial models to the class, and the instructor facilitates a discussion in which students share their ideas. The instructor does not contribute ideas, but encourages students to think about what evidence they can collect in the laboratory to test their models. The vast majority of students initially expect to observe the formation of a shiny, bulk gold precipitate when synthesizing gold nanoparticles.

During the module, small groups of students participate in several iterations of MORE. Students conduct experiments, reflect upon how the evidence collected relates to their models, participate in class discussions, and refine their models. In part I, students use laser pointers to observe the scattering of light in familiar aqueous solutions and colloidal mixtures (see photo, panels A and B) and interpret the evidence they collect to propose molecular-level pictures of each. Next, student groups synthesize gold nanoparticles, varying the amount of sodium citrate used such that different-sized nanoparticles are produced. Students again use laser pointers to collect evidence related to the nature of the reactants (C) and products (D and E in the photo), which are solutions and colloidal mixtures, respectively. An example illustrating how one student refined her model to be consistent with the evidence she collected is shown in section A of the table.

During part II, students view a live demonstration or computer animation of an atomic-force microscope (AFM). Groups are then provided with AFM images of the reaction mixtures from the previous experi-

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ments, and students characterize the features of the images (e.g., the heights of the structures) and further refine their models of gold nanoparticles (sections B and C of the table).

In part III, students predict what will happen when aqueous solutions of potassium iodide and dextrose are added to a gold nanoparticle mixture (*8*). They then conduct experiments to test their predictions and further refine their models. Students predict what AFM images of their mixtures will look like and subsequently view and analyze those images.

In the final part of the module, students explore the use of gold nanoparticles as optical biosensors by designing a pregnancy test similar to a real-world urine test. The proposed mechanism behind the test is that higher levels of protein, such as the pregnancy hormone human chorionic gonadotropin, bind to the surface of gold nanoparticles and reduce salt-induced aggregation, which results in a color difference relative to lower levels of protein (*9*, *10*). For this part of the module, each laboratory section is provided with 60 ml of a colloidal gold nanoparticle mixture and synthetic urine samples from two fictitious women (one pregnant and one not). The students must work together to design a pregnancy test that reliably distinguishes the samples.

Given students' initial lack of familiarity with nanoscience, there is great potential for them to develop an understanding of this topic in introductory science courses. The Exploring Gold Nanoparticles module effectively guides students to develop models of these systems. Most students successfully revise their initial models to be consistent with the evidence they collect, as well as with scientifically accepted views. In the process of constructing their own evidence-based models, as opposed to simply being presented with the expert model, students not only learn about the process of science, but also enhance their understandings of the systems they study. This makes it more likely that students will be able to effectively build upon their models and apply them in new contexts, including more advanced courses and research.

About the authors



A. Colin Blair earned his B.A. in Chemistry from Hendrix College, where he minored in English, and has a M.S. in Chemistry from Colorado State University. He has studied high-resolution infrared spectroscopy of transient species and students' beliefs about learning. **Ellen R. Fisher** is a Professor of Chemistry at Colorado State University where she studies materials chemistry, plasma science, and nanomaterials. She is interested in responsible conduct of research education and has developed inquiry-based materials for analytical chemistry courses. She is an associate editor of the American Chemical Society's ACS Applied Materials and Interfaces. **Dawn Rickey** is an Associate Professor of Chemistry at Colorado State University studying how people learn with a depth of understanding that enables them to apply scientific models effectively in new contexts. Rickey codeveloped the MORE Thinking Frame as part of her graduate work at the University of California, Berkeley.

A. First Refined Model (following Part I: What are nanoparticles?)

"…After mixing, each of the solutions changed colors. [Mixture] A became a cloudy brown color (blue when held up to the light), [mixture] B became purple, and [mixture] C became red…. I had expected to see a gold precipitate, but nothing was visible. However, we were able to see the laser beam through all of the solutions, which tells me there had to be particles floating in the solution for the laser to reflect off of (even though we can't see them)…. I thought all of the solutions would be the same and would produce a gold precipitate of the same amount. We did not find the solutions to be the same. Due to the three different colors, there appears to be 3 different substances formed. As for the gold, I believe that it doesn't just separate into individual gold molecules. I think the Au molecules cluster together while floating and that these clusters are the 'nanoparticles.' This explains why we can see the laser beam in the solutions—the clusters of Au molecules give the beam something to bounce off of so we can see it…. I think the laser is bouncing off clusters of particles that are bigger than regular molecules."

B. During-Lab Reflection (following Part II: Using AFM Images to Refine Your Model)

"The citrate was the only thing that was varied so that means the citrate effects [sic] the way the gold clumps together. In [mixture] A, they were the biggest clumps, in C they were the smallest…. The particles are bigger than a single gold atom, which means it is a clump of many gold atoms."

C. Final Refined Model (following completion of all parts of the module)

"…I thought all of the solutions would look the same with the AFM. However, this was wrong…. I believe the nanoparticles are actually clumps of Au molecules and the bigger ones are just more Au molecules clumped together…."

Student model excerpts. Excerpts from one general chemistry student's laboratory reports showing how she refined her model of gold nanoparticles.

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References and Notes

1. President's Council of Advisors on Science and Technology, *Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics* (White House, Washington, DC, 2012); www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_feb.pdf.
2. L. T. Tien, D. Rickey, A. M. Stacy, *J. Coll. Sci. Teach.* **18**, 318 (1999).
3. L. T. Tien, dissertation, University of California (1998).
4. D. Rickey, dissertation, University of California (1999).
5. The complete Exploring Gold Nanoparticles laboratory manual is available as Supplementary Materials.
6. D. L. Schwartz, C. C. Chase, M. A. Oppezzo, D. B. Chin, *J. Educ. Psychol.* **103**, 759 (2011).
7. A. C. Mattox, B. A. Reisner, D. Rickey, *J. Chem. Educ.* **83**, 622 (2006).
8. A. D. McFarland, C. L. Haynes, C. A. Mirkin, R. P. Van Duyne, H. A. Godwin, *J. Chem. Educ.* **81**, 544A (2004).
9. V. Wiwanitkit, A. Sereemaspun, R. Rojanathanes, *Ren. Fail.* **29**, 1047 (2007).
10. R. Rojanathanes *et al.*, *Taiwan J. Obstet. Gynecol.* **47**, 296 (2008).

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Supplementary Materials

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