JOURNAL OF CHEMICAL EDUCATION

Article

pubs.acs.org/jchemeduc

# Increasing Interactivity and Authenticity of Chemistry Instruction through Data Acquisition Systems and Other Technologies

Marina Milner-Bolotin*

Department of Curriculum and Pedagogy, University of British Columbia, Vancouver, BC, Canada V6T 1Z4

**ABSTRACT:** Interactivity and inquiry-based learning science are effective ways of helping students overcome their perception of chemistry as an alien and abstract topic and instead approach the subject as a creative way of understanding ideas and applying mastered concepts to new contexts. Data acquisition systems are an extremely useful form of educational technology that can be used alone or in conjunction with other technologies to bring about active learning and enable students to move beyond memorization to the verification strategies and knowledge base they need to successfully master chemistry concepts. This article describes the use of data acquisition systems and analysis software in combination with other technologies such as electronic response systems and online video. The technologies were used for laboratory activities, online learning, and lecture hall demonstrations and allowed for cross-disciplinary experiments. They also brought an element of interactivity to each instructional setting that proved to be an excellent avenue for engaging student interest and ensuring comprehension of chemistry topics.

**KEYWORDS:** *First-Year Undergraduate/General, Curriculum, Demonstrations, Interdisciplinary/Multidisciplinary, Inquiry-Based/Discovery Learning, Instrumental Methods, Laboratory Equipment/Apparatus, Student-Centered Learning*

There is evidence that inquiry-based teaching has the potential to help students overcome their fear of science and motivate them to pursue science as a career.[1] Inquiry-based pedagogy encourages students to approach science as a creative way of understanding the world by applying the concepts learned in class to relevant contexts, either in their everyday life or in the lab.[2−7] However, post-secondary educators who attempt to implement inquiry-based learning in their classrooms face two major challenges: the growing class size of undergraduate introductory science courses and their increased breadth. These challenges leave little time for scientific inquiry that is reflective of the scientific process, thus, forcing instructors to sacrifice the quality of student learning in order to "cover" more material. How can university and college science instructors incorporate interactivity and scientific inquiry into large-class science lectures without sacrificing the bulk of class time to the repetitive task of traditional manual data collection?

Although institutions have varied strategies for addressing these challenges, many schools are utilizing technology to help students take part in scientific thinking processes and gradually build an understanding of abstract science concepts.[8−16] One method is to help students develop science problem-solving skills through immersing them in an active learning environment rather than having them passively memorize rules and principles.[14,17−21] Although the emphasis on active learning in the sciences began more than 40 years ago in the physical sciences,[22] it gradually spread to the other disciplines, including chemistry education.[8,12,23−27] Data acquisition systems are an educational technology that can be used alone or in conjunction with other technologies to bring about active learning and enable students to move beyond rote memorization.

The data acquisition systems consist of a range of high-technology measuring tools such as probes, sensors, and meters that may operate independently or connect to a computer interface. The different sensors enable experimental data to be automatically entered into a computer or handheld device instead of requiring participants to manually log multiple data points. The automatic transfer of data points to tables, graphs, and calculated columns makes it possible for swift and accurate analysis, so students can focus on interpretation of the live data rather than its manual collection. This allows students to gain valuable insights and experience the process of scientific inquiry during large lecture classes and not only in labs or tutorials.

This article describes the use of sensors and analysis software from Vernier Software & Technology[28] alone and in conjunction with other technologies. However, electronic data acquisition equipment from other manufacturers can also be used. The sensors and software were used for laboratory activities, problem-solving sessions (tutorials), homework assignments, and during large lecture classes. Employing such equipment to bring scientific inquiry via data collection and analysis to the four instructional settings has proven to be an excellent avenue for engaging student interest and ensuring comprehension of chemistry and other sciences.[24,25,29]

During the last decades of the 20th century, a number of science teachers and educational researchers argued for the traditional methods of manual data collection, stating that performing such tasks by hand promotes a better understanding of the task.[30] However, as students and teachers became more adept at using new technologies and those technologies became more pervasive, the counterargument for the use of educational technologies in science classrooms gained momentum. Currently, it is widely accepted that comprehension of the actual subject comes from meaningful

**Published:** February 15, 2012

experimental design and data analysis rather than repetitive data collection.[1]

Additionally, resetting the parameters of a science experiment, manually recording the independent and controlled variables, and then creating graphs is time-consuming. Such tedious activities can cause students to mentally disengage before the end of the project. Another time-related concern is that when students conduct manual data collection, they take a long time to get to the part of the lesson where they interpret the results and make predictions, which might reduce the time the students can dedicate to inquiry-based learning. With sensors and related software packages, the task of data collection and analysis has become more accurate, quick, and straightforward.

Students who pursue careers in science and engineering will be using cutting-edge technology tools to collect and analyze data, so exposing them to these tools will be helpful. Moreover, an opportunity to display data in multiple forms (such as graphs and tables) during the data collection process helps students build their scientific intuition. Students can vary experimental parameters and immediately see the changes reflected in the graphs. Consequently, students can explore different aspects of a concept, make predictions about the effects of these changes, and test their ideas instead of spending their time and attention on manual data collection. It is also important to emphasize the difference between incorporating virtual science labs using computer simulations[10,19,31−33] and conducting real-time data collection using sensors. Although virtual learning has its merits, it is not equivalent to the students exploring real-life experiments and getting their hands wet with “bench science”.

## ■ APPLICATIONS OF SENSORS AND CLICKERS IN THE CLASSROOM

One of the challenges of traditional lectures in large, fast-paced introductory science courses is that students usually do not have time to process and integrate new information and are forced to passively accept it, hoping to do the integration at home. Science instructors have attempted to address this issue by bringing data acquisition systems and other lab equipment into large lecture classes to demonstrate experiments during lectures and have students ask questions about the demonstrations.[15,34−36] However, many instructors have reported that the passive act of simply observing a demonstration was insufficient to provide students with an accurate understanding of the phenomena they witnessed.[15,37,38]

Those reports were tested by conducting an experiment with two groups of 250 science majors in an introductory physics course.[15,34] The students explored a challenging concept: the variations of the tension force in the string of an oscillating pendulum. Although the experiment was conducted in a physics course, the sensor-enhanced pedagogy[15] is applicable to other science classes, including chemistry.

In the first section, a traditional pedagogy was used for the in class demonstration; the instructor explained the concept and demonstrated it to the class using a pendulum connected to a large mechanical scale. The students asked questions, discussed the concept in small groups, and answered multiple-choice questions related to the concept using electronic response system (clickers). A few weeks later, the students had a multiple-choice midterm exam that included the same concept as one of the exam items. Only 25% of the students who observed the lecture demonstration were able to answer the question correctly, and 59% chose the same incorrect response. During the follow-up interviews, the students verified that they did not remember what they saw during the lecture demonstration, but only what they expected to see. The demonstration failed to help the majority of the students replace their pre-existing misconceptions with the scientifically correct ones. This is not surprising as the students were not engaged in the direct cognitive conflict required to correct their erroneous prior beliefs.[39,40]

In the second section, sensors were used in conjunction with the clickers for the creation of what has been termed “interactive lecture experiments”.[15] The students who were taught using this method showed significant improvements in the accuracy of their understanding of the concepts. The interactive lecture experiment pedagogy is a modification of the “interactive lecture demonstrations” proposed in the 1990s by Sokoloff and Thornton.[21] Interactive lecture experiment pedagogy involves three stages. In the first stage, which takes place during the first lecture, the instructor sets up an experiment and asks the students to make and record their predictions regarding its outcome. These predictions have both qualitative and quantitative components, thus, requiring students to rely on relevant measurements. Then, the experiment is conducted in the lecture, and appropriate sensors are used to collect and record necessary data. During the second stage, which takes place outside of the classroom, the students are asked to analyze the data collected during the lecture and draw relevant conclusions to answer the original question. The culmination of the interactive lecture experiment activity takes place during the follow-up lecture (the third stage), when the students bring their analysis results and share them with the class using clickers. Students’ responses are collected electronically and a histogram of their responses is displayed. Then, the professor uses relevant data collection equipment to verify which predictions and analysis were accurate. This is followed by an all-class discussion.

Combining the use of sensors with the use of clickers to allow students to make and test their predictions turned lectures into interactive learning experiences that helped students to stay focused and accurately remember the experimental outcomes.[15] More than 50% of the students who participated in those classes answered the relevant question correctly on their midterm exams as compared to 25% of the students in the first section. Furthermore, the students showed an improved ability to explain and solve traditional open-ended problems in their final exams.[15]

Teachers who desire a change of pace for classes can also use their high-technology data collection and analysis tools to incorporate online learning into their curriculum. Research indicates that online simulations or videos used in conjunction with hands-on experiments generate higher levels of learning outcomes compared to the same hands-on experiments provided alone;[41−43] this same reasoning should apply to the use of videos in the classroom. Instructors can create video clips of their lecture demonstrations and upload the recordings, along with data collected via the sensors, onto the Web for students to access. After the lecture, students download the data to perform further analysis and work in small groups to come up with answers to provided questions. The extra time spent working on video analysis[43,44] helps students to develop a deeper conceptual understanding and uncover and confront possible misconceptions. In the next class, the students submit their answers via the clickers in addition to providing a brief written report and participating in a class discussion.

## APPLICATIONS OF SENSORS IN THE LAB

Traditionally in the labs, students were only able to collect a few data points and create graphs with limited accuracy, causing them to believe they could not do “real science”. Data acquisition systems allow students to collect more accurate and complete experimental data and, if necessary, redo the data collection as the task takes relatively little time. Using data-collection tools also leaves time for testing other hypotheses and asking and answering “what-if” questions that could not be easily answered in a low-tech lab. Additionally, science instructors can use sensors for generating authentic exam problems instead of resorting to fake problems with perfect but unrealistic data.[45]

## TWO EXAMPLES OF INQUIRY-BASED ACTIVITIES USING DATA ACQUISITION SYSTEMS

Data acquisition systems completely change how instructors teach science and how students learn it. The probes can be linked to interfaces and also graphing calculators, allowing for the natural linking of mathematics and science. Instructors can also use graphing calculators to facilitate video analysis via online trackers. Whereas instructors were previously just talking about mathematics, thorough mathematical analysis can now be seamlessly incorporated in classroom activities. In addition, the equipment allows for projects that cross disciplinary fields such as physics and chemistry, which reflects modern science much more closely.

### Relative Humidity and the Psychrometric Chart

For three terms, architecture students participated in a set of large-class activities during a general physics lecture course. The goal of these activities was to help the students learn fundamental physical and chemical concepts and laws applicable to architectural science, such as ideal gas laws, chemistry of air−water mixture, partial pressure, dew point, relative humidity, and a psychrometric chart. Specifically, the aim of teaching the concepts of relative humidity and the psychrometric chart reading was to help the students grasp the concept of humidity and its applications to architectural design. The students were asked to explore the following questions: (a) How can one measure humidity using a thermometer and a psychrometric chart? and (b) What are the differences between the dry bulb and wet bulb temperatures used in a psychrometric chart?

During the lecture, the instructor used a Vernier temperature probe[28] connected to a computer that projected readings on a large screen. Taking a glass of water and a napkin, the instructor first completely moistened the napkin and then placed it so that one end was submerged in the glass of water while the other end was wrapped around the temperature probe. This way, the napkin stayed wet during the experiment. The temperature probe, the water, and the napkin were left in the classroom until they reached an ambient temperature. Then, the instructor invited a student volunteer to start data collection.

Initially, the probe displayed an ambient temperature of 19.8 °C. However, as the water started evaporating from the napkin, the temperature probe started detecting a gradual drop in temperature. Lower humidity in the room produced a stronger evaporation rate and a more significant temperature drop. For example, in the experiment, the temperature dropped from 19.4 to 17.0 °C in correspondence to the relative humidity of about 76%, which the students were able to determine using a pscyhrometric chart in their textbooks. Then, the instructor used a standard hygrometer to verify the results of the experiment. This experiment helped students understand the idea of dry bulb (ambient) temperature versus wet bulb temperature and the concept of psychrometry, which are often stumbling blocks for students. The activity led to other questions that the students had about relative humidity; for example, the need for humidifiers during cold winters, the reason for feeling so hot during humid summers, and the reason why relative humidity must be taken into account in living spaces.

### Radioactive Decay

Another example of an interactive chemistry activity using a sensor focused on understanding radioactive decay, the concept of random radioactive emission, and the principle of radioactive dating. This activity used a Vernier Geiger counter and a number of radioactive materials such as a luminous radioactive watch, “NoSalt” salt, and a piece of a Fiesta dishware. The instructor explained how the Geiger counter worked and suggested measuring the background radioactivity level. Interestingly, the majority of the students (future middle school teachers in a science methods class) were not aware of the background level of radiation. While the sensor was collecting the background data, the students and instructor were able to engage in a discussion. In a traditional lab, the students would have been manually collecting data every 10 s (that was the choice for the activity) and recording the data in their lab books. Because this tedious work was delegated to a computer, the students were able to engage in a more meaningful discussion. For example, the instructor asked the students to predict the next reading of the Geiger counter. This task was meant to emphasize that radioactive decay is random process on a single atom level and it is impossible to predict when the nuclei are going to decay. As the data collection proceeded, the students were able to realize that despite the lack of pattern, on average, more radioactive objects produce a higher number of decays per unit time. During the activity, the students were able to ask questions related to radioactive decay and radioactive dating, as well as design experiments to generate their own answers.

## CHALLENGES OF USING DATA ACQUISITION SYSTEMS IN DESIGN AND IMPLEMENTATION OF INQUIRY-BASED SCIENCE LESSONS

Overall, the difficulty that instructors are most likely to encounter with sensors is not in the actual use or explaining its usage to students, but rather devising meaningful and exciting ideas for activities. Instructors looking for activities involving data acquisition systems can find ideas from the Resources for Chemistry Educators Web site,[46] the National Science Teachers Association,[47] workshops from Vernier Software & Technology,[28] this *Journal*,[48−51] the Biennial Conference on Chemical Education, and books such as *Chemical Education: Toward Research-Based Practice*[52] and *The Chemist’s Guide to Effective Teaching*.[53] The workshops, in particular, present opportunities to learn how to use equipment.

Because many chemistry topics overlap with physics, educators may also consider attending the American Association of Physics Teachers (AAPT) workshops as well as accessing the Web site for the comPADRE partnership of physics and astronomy education committees.[54] Another option that university instructors have is downloading sample labs via the Web site for Vernier, as well as posting questions at its discussion forum[55] for other science teachers or company staff to answer.

## ■ SUMMARY

The advantages of using data-collection probes and interfaces are fourfold: (a) students are exposed to more questions than was traditionally possible, (b) the equipment allowed them to gather tangible evidence of phenomena that would have been too quick or too small to detect without instrumentation, (c) students can test ideas in a way which previously had been too time-consuming for a regular class period, and (d) the increased opportunities for making predictions and performing data analysis helps keep the students focused and gives them a measure of autonomy over their own learning.

Students have responded well to these innovative forms of instruction, and the impact of these reforms has resulted in higher student attendance and success rates along with positive course evaluations, effects that have been reported by educators at other institutions.[56] To maintain and expand the positive educational effects of inquiry-based instruction using sensors, we are currently working on designing and implementing professional development activities for future teachers that utilize sensors and other data analysis technologies.

## ■ AUTHOR INFORMATION

### Corresponding Author

*E-mail: marina.milner-bolotin@ubc.ca.

## ■ REFERENCES

(1) Hofstein, A.; Lunetta, V. N. *Sci. Educ.* **2004**, *88*, 28−54.

(2) Herron, J. D. Research in Chemical Education: Results and Directions. In *Toward a Scientific Practice of Science Education*; Gardner, M., Greeno, J. G., Frederick, R., Schoenfeld, A. H., DiSessa, A., Stage, E., Eds; Lawrence Erlbaum Associates: Hillsdale, NJ, 1990; pp 31−54.

(3) Schoenfeld, A. H., GRAPHER: A Case Study in Educational Technology, Research, and Development. In *Toward a Scientific Practice of Science Education*; Gardner, M., Greeno, J. G., Frederick, R., Schoenfeld, A. H., DiSessa, A., Stage, E., Eds; Lawrence Erlbaum Associates: Hillsdale, NJ, 1990; pp 281−300.

(4) Farrell, J. J.; Moog, R. S.; Spencer, J. N. *J. Chem. Educ.* **1999**, *76*, 570−574.

(5) Trends in International Mathematics and Science Study (TIMMS). National Center for Education Statistics. http://nces.ed.gov/timss (accessed Feb 2012).

(6) Clemens-Walatka, B. *Sci. Teach.* **1998**, *65* (1), 21−23.

(7) TIMSS and PIRLS International Study Center TIMSS and PIRLS. http://timssandpirls.bc.edu (accessed Feb 2012).

(8) Lee, H. S.; Linn, M. C.; Varma, K.; Liu, O. L. *J. Res. Sci. Teach.* **2010**, *47*, 71−90.

(9) Teese, R. LivePhoto Physics Project. http://livephoto.rit.edu (accessed Feb 2012).

(10) Campbell, T.; Wang, S. K.; Hsu, H.-Y.; Duffy, A. M.; Wolf, P. G. *J. Sci. Educ. Technol.* **2010**, *19*, 505−511.

(11) Peters, L. *Global Education: Using Technology To Bring the World to Your Students*; International Society for Technology in Education: Eugene, OR, 2009.

(12) Varma, K.; Husic, F.; Linn, M. C. *J. Sci. Educ. Technol.* **2008**, *17*, 341−356.

(13) Reins, K. Digital Tablet PCs as New Technologies of Writing and Learning: A Survey of Perceptions of Digital Ink Technology. *Contemp. Issues Technol Teach. Educ.* **2007**, *7*, 158−177.

(14) Hoffman, C.; Goodwin, S. A clicker for your thoughts: technology for active learning. *New Libr. World* **2006**, *107*, 422−433.

(15) Milner-Bolotin, M.; Kotlicki, A.; Rieger, G. *J. Coll. Sci. Teach.* **2007**, *36* (4), 45−49.

(16) Milner-Bolotin, M. T *Phys. Teach.* **2004**, *42*, 47−48.

(17) Kalman, C. S.; Milner-Bolotin, M.; Antimirova, T. Comparison of the effectiveness of collaborative groups and peer instruction in a large introductory physics course for science majors. *Can. J. Phys.* **2010**, *88* (5), 325−332.

(18) Reba, M.; Weaver, B. Tablet PC-Enabled Active Learning in Mathematics: A First Study. *First International Workshop on Pen-Based Learning Technologies, PLT 2007*: 2007, 1−6, 10.1109/PLT.2007.38.

(19) Perkins, K.; Adams, W.; Dubson, M.; Finkelstein, N.; Reid, S.; Wieman, C.; LeMaster, R. *Phys. Teach.* **2006**, *44*, 18−23.

(20) Christian, W.; Belloni, M. *Physlet Physics: Interactive Illustrations, Explorations, and Problems for Introductory Physics*; Pearson Education: Upper Saddle River, NJ, 2004; p 326.

(21) Sokoloff, D. R.; Thornton, R. K. *Interactive Lecture Demonstrations: Active Learning in Introductory Physics*; John Wiley and Sons: New York, 2004.

(22) DeBoer, G. E. *A History of Ideas in Science Education: Implications for Practice*; Teachers College Press: New York, London, 1991; Vol. *1*, p 270.

(23) Tofan, D. S. *J. Chem. Educ.* **2009**, *86*, 1060−1062.

(24) Cooper, M. M.; Kerns, T. S. *J. Chem. Educ.* **2006**, *83*, 1356−1361.

(25) Sereda, G. Teaching Organic Chemistry to Students with Diverse Academic Backgrounds. *Chem. Educator* **2005**, *10*, 46−49.

(26) Felder, R. M. In *Beating the Number Game: Effective Teaching in Large Classes*; Proceedings of ASEE Conference, Milwaukee, WI, June 1997; pp 36−40.

(27) Basili, P. A.; Stanford, J. P. *J. Res. Sci. Teach.* **1991**, *28*, 293−304.

(28) Vernier Software & Technology Logger Pro 3. http://www.vernier.com/soft/lp.html (accessed Feb 2012).

(29) Piquette, J. S.; Heikkinen, H. W. *J. Res. Sci. Teach.* **2005**, *42*, 1112−1134.

(30) Tobin, K. *Sch. Sci. Math.* **1990**, *90*, 403−418.

(31) Milner-Bolotin, M.; Antimirova, T. Enhancing Student Learning: Using Tablet PCs in Modern Physics Class. Proceedings of 2010 American Association of Physics Teachers Winter Meeting, Washington, DC, February 13−17, 2010; American Institute of Physics.

(32) Liu, X. *J. Sci. Educ. Technol.* **2006**, *15*, 89−100.

(33) Finkelstein, N. D.; Adams, W. K.; Keller, C. J.; Kohl, P. B.; Perkins, K. K.; Podolefsky, N. S.; Reid, S.; LeMaste, R. *Phys. Rev. Spec. Top.—Phys. Educ. Res.* **2005**, 1.

(34) Moll, R.; Milner-Bolotin, M. *Can. J. Phys.* **2009**, *87*, 917−924.

(35) Sokoloff, D. R.; Thornton, R. K. *Phys. Teach.* **1997**, *35*, 340−347.

(36) Robertson, W. W. *Am. J. Phys.* **1949**, *17*, 19−21.

(37) Milner-Bolotin, M. An Ultimate Elevator Ride: Weight and Apparent Weight Demonstration. *Newsletter of the Ontario Association of Physics Teachers* November **2008**, pp 1−2.

(38) Crouch, C. H.; Fagen, A. P.; Callan, J. P.; Mazur, E. *Am. J. Phys.* **2004**, 72, 835−838.

(39) Kalman, C. S.; Aulls, M.; Rohar, S.; Godley, J. *J. Coll. Sci. Teach.* **2008**, *37* (3), 74−81.

(40) Limon, M. On the Cognitive Conflict as Instructional Strategy for Conceptual Change: A Critical Appraisal. *Learn. Instruct.* **2001**, *11*, 357−380.

(41) Casanova, R. S.; Civelli, J. L.; Kimbrough, D. R.; Heath, B. P.; Reeves, J. H. *J. Chem. Educ.* **2006**, *83*, 501−507.

(42) Brown, D.; Cox, A. J. *Phys. Teach.* **2009**, *47*, 145−150.

(43) Antimirova, T.; Milner-Bolotin, M. A Brief Introduction to Video Analysis. *Physics in Canada*, April−May **2009**, *65*, p 74.

(44) Milner-Bolotin, M.; Antimirova, T. Video Analysis in Science and Engineering Education, Proceedings of *EDULEARN10*, Barcelona, Spain, July 5−7, 2010; Chova, L. G.; Belenguer, D. M.; Torres, I. C.,

Eds.; International Association of Technology, Education and Development (IATED): Barcelona, Spain, 2010; pp 004770−004776.

(45) Milner-Bolotin, M.; Moll, R. F. *Phys. Teach.* **2008**, *46*, 494−500.

(46) Lower, S. Resources for Chemistry Educators, 2011. Steve Lower's Web site http://www.chem1.com/chemed (accessed March 31, 2011).

(47) National Science Teachers' Association Home Page. http://www.nsta.org/. (accessed Mar 2011).

(48) Cortés-Figueroa, J. E.; Moore-Russo, D. A.; Schuman, M. J. *Chem. Educ.* **2006**, *83*, 64−68.

(49) Hudgins, S.; Qin, Y.; Bakker, E.; Shannon, C. *J. Chem. Educ.* **2003**, *80*, 1303−1307.

(50) Ealy, J. B.; Negron, A. R.; Stephens, J.; Stauffer, R.; Furrow, S. D. *J. Chem. Educ.* **2007**, *84*, 1965−1967.

(51) Sales, C. L.; Ragan, N. M.; K., M. M. *J. Chem. Educ.* **2001**, *78*, 694−696.

(52) Nakhleh, M. B.; Polles, J.; Malina, E. Learning Chemistry in a Laboratory Environment. In *Chemical Education: Toward Research-Based Practice*; Gilbert, J. K., De Jong, O., Justi, R., Treagust, D. F., Van Driel, J. H., Eds.; Kluwer Academic Publishers: Dordrecht, Netherlands, 2003; pp 69−94.

(53) Pienta, N. J.; Amend, J. Electronic Data Collection To Promote Effective Learning during Laboratory Activities. In *Chemists' Guide to Effective Teaching*; Pienta, N. J., Greenbowe, T. L., Cooper, M. M., Eds.; Prentice-Hall: New York, 2005; pp 172− 185.

(54) comPADRE Home Page. www.compadre.org (accessed Jan 2011).

(55) Vernier Vernier Discussion Forum, 2006. http://www.vernier.com/discussion (accessed Feb 2012).

(56) Mazur, E. *Science* **2009**, *323*, 50−51.