Guiding Chemistry Students with Essential Questions

SUMMARY

This article outlines the shift in a 10th–12th grade Regents Chemistry classroom from traditional lecture and lab lessons to more student-centered, student-driven, differentiated inquiry-based lessons. Integrating these methods in science class and lab instruction provides the opportunity to meet the students where they are while increasing student engagement and understanding.

The chemistry classroom is a busy, active place.

In one area, students conduct an experiment. While one group answers guided-inquiry questions, another group clusters around the whiteboard to record their explanations, and still a different group excitedly discusses their findings. All of the students are at various levels academically, yet all are independent, motivated and highly engaged in constructing knowledge.

This is a far cry from how I first began teaching — the days of "traditional" lecture, PowerPoint, and book work routines; the classroom where consistent content retention was lacking, cheating on quizzes and homework assignments was rampant (Loschiavo, 2015), and true student-to-student collaboration was missing.

While my students' Regents results were decent (average 77 with 25 percent mastery) and retention in future classes was strong (60 percent), I knew piquing student interest in science to higher levels would open doors for them.

After reading a 2003 National Research Council Report that indicated 40 percent of high school students are chronically disengaged from school (Council, 2003) and subsequent reports that show disengagement among students is growing (Sheehy, 2013), I shifted focus to create an environment that fosters more active student engagement. Inquiry, the National Science Education Standards (Olson, 2000), and the National Science Teachers Association recommendations (Association, 2004) guided me in developing appropriate activities that teach skills, such as questioning, developing investigations, critically analyzing

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The inquiry process drives student engagement by leveraging student's natural curiosity about the world around them. It helps students to develop the need to know.

findings, clearly communicating results, and working with others as a part of a team. These skills transcend multiple career fields and are valued by many employers (Adams, 2014).

The inquiry process leverages a student's natural curiosity about the world. It helps students develop the need to know. This, in turn, gets students involved in learning at cognitive, behavioral, and sometimes, even emotional levels. Interest and involvement also help make the concepts relevant.

Research and standards alone cannot drive student achievement. Awareness and analysis about barriers of inquiry integration (Cheung, 2006), such as stimulating interest, forming effective groups where each member contributes, making sure activities are at the appropriate level for all of my students and verifying student progress as they learn the material, led me to develop strategies to navigate potential hurdles.

To start, I utilize unit-centered essential questions, as recommended by McTighe and Wiggins. The questions are designed specifically to guide students in stimulating thought and to provide an overarching unit theme centered around student interests (McTighe & Wiggins, 2013). As the questions link topics of student interest to the content, they develop and deepen student understanding and serve as a lens through which students see and discover the topic. The variety of answers to the essential questions allow for unique student responses. For example, essential questions such as, "How does the structure of organic compounds in food impact the flavor?" prompt questions from the student groups — "What are our favorite foods?" "What organic functional groups are present in them?" — that drive both student engagement and the inquiry process. Groups may work on different essential questions for the same unit.

Process Oriented Guided Inquiry Learning (POGIL) is a large cornerstone to reinforce key concepts relating to the essential question. The method uses guided inquiry — a learning cycle that explores a graphic or computer animation and convergent questions to aid in concept invention and application as the basis for materials that students use to guide them to new knowledge.

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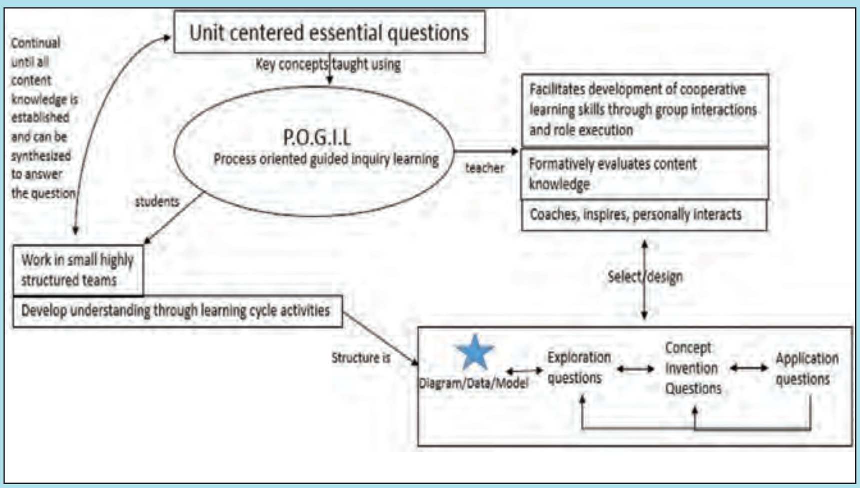
In an activity where the essential question is "How does light reveal the behavior of electrons in an atom?" students start by answering questions about a provided energy, wavelength and speed of light chart. Building on their exploration question responses, students invent the concept that as photon energy increases, the wavelength of light decreases. Application of this newly "invented" concept occurs after students "invented" the origin of spectral lines. The two concepts are then combined with the application extension question: "The spectral lines for atoms are like fingerprints for humans. To what extent can this method be used to provide information about the age of stars in space? How could this work?" These activities often accompanied by students exclaiming, "Oh! The pattern is…" and "Wow! I never knew how they could tell the age of stars!"

Process Oriented Guided Inquiry Learning (POGIL)



The activities focus on content knowledge of core concepts in chemistry with several activities per unit closely aligned with the New York State Chemistry Standards. Activities also develop higher-order thinking skills and a deep understanding of material (Spencer & J.N, 2006). I use many developed materials as I write my own. The POGIL activities combine the three dimensions of the Next Generation Science Standards in my classroom:

- Disciplinary Core Ideas (DCIs) that are developed within the activity;
- Science and Engineering Practices (SEPs) where students are probed to develop or design a solution; and
- Crosscutting Concepts (CCs) that are integrated during the concept invention and application questions (Next Generation Science Standards, 2016).

The effectiveness of the POGIL activity hinges on the purposeful grouping of students. This allows for personalized instruction and for students to develop a supportive community in the classroom. For grouping, I follow guidelines from the Cooperative Learning Institute (Johnson, 2016). Groups of three to four students work together on the essential questions and learning materials. Groups are homogeneous if content knowledge is going to be a "separating factor." I alleviate knowledge differences by embedding additional

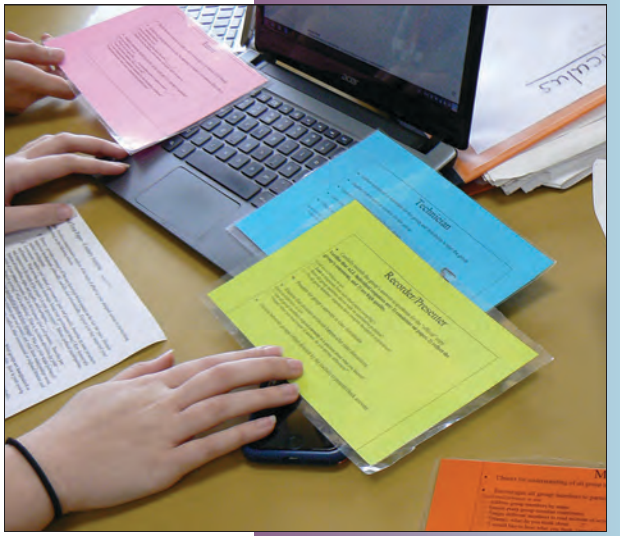
chemistry-specific scaffolding into student activities (Sloop, 2016).

Heterogeneous groups are used when diverse viewpoints and ideas will strengthen the development of concepts that are new to most students based on pre-test information aligned with Cooperative Learning Institute recommendations (2006). New groups are formed once or twice a quarter.

Initially, student groups struggled to work together. The upper-level students started to work individually — "I can do this by myself" — while the middle/lower level students would either write down responses or copy responses — "I know this." I now teach students the skills necessary to work in groups effectively:

- clear communication,
- listening,
- courteous interactions,
- taking responsibility,
- accepting feedback, and
- dealing with conflict (Bosworth, 1994).

Students discuss what these skills look like from their perspective and mine. As these conversations take place, students acknowledge: "It helps to know how we should work in a group." When needed, we employ brainstorming strategies to ensure everyone practices skills for effective group work. To further facilitate group work, I assign roles (see below) to provide structure and to create pro-social behaviors associated with working in cooperative groups (Hanson, 2006). Specific roles are selected and assigned to students for each activity. All of the roles are not used in each instance. Students are provided a visual card and their knowledge of what to do is assessed prior to starting the activity.



During the class period I hear students say: "We have three minutes left for this section" or "What are your answers? How do they connect?" or "Do we all have something similar? Let's move on."

Student Workgroup Roles

Manager or Facilitator: Ensures that members are fulfilling their roles and participating, and assigned tasks are being accomplished on time.

Recorder: Records the important aspects of the group discussions, observations, insights, etc. Shares information with others as needed.

Spokesperson (Presenter): Presents oral reports to the class.

Stategy analyst (Reflector): Observes and comments on the group dynamics and behavior with respect to the learning process.

Quality Control: Verifies that ALL individual responses are consistent on paper, and reflect group's consensus. Ensures that accurate revisions happen if needed.

Technician: Performs all technical operations for the group, including the use of a calculator or computer.

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Shifting to inquiry in class led to more engaged students, and higher quality and quantity of work the students completed.

After the activity, students reflect on how they implemented their role using an evidence/improvement form, process analysis form, or by writing out areas of strengths, improvements and insights. The clarity a role provides gives students parameters for working within groups. They know what they have to do as well as what their group mates need to do. The combination of roles and reflection gives students a concrete task they are accountable for during the activity.

Differentiating instruction

Differentiation within learning activities levels the class. Questions students are asked to complete are given various shapes — stars and squares, for example, — based on the student's level. I build in additional exploration questions for students who may struggle, while advanced students quickly get to complex open-ended questions. Open-ended questions are designed to stimulate discussion. For an activity on the differences in acid and base concentrations, a question about how the pH changes within your digestive system can impact the breakdown of food, stimulates in-depth student discussion. If students are comfortable with the question, they could skip those marked by stars. Struggling students are able to skip the questions marked by squares. Directions about the activity and an explanation of the shapes are contained in the packet of the questions and on the whiteboard. Other methods of differentiation include having students select an application question or application activity out of a colored container that is divided by difficulty level, interest, or another factor.

Assessing individual accountability

Most student assessments are formative (Marzano, 2009) and simply provide a means for demonstrating the knowledge they have gained. Assessing individual student accountability gauges student understanding, their engagement during the activity and whether the level of rigor was appropriate for them. Some techniques I use for individual student assessment include:

- Students take a short quiz at the end of an activity.
- Students develop a review sheet from key questions.
- Students write details about their activity on the whiteboard.
- Students write a one- or two-sentence summary or reflection.
- Use graphic organizers to help students reflect on the content they learned.
- Debrief the next day as a formative assessment.
- Students break down their process for solving a problem into specific steps.

Student reflections are used to inform instruction and to improve student learning. Following guidelines from McDonald and Boud, such as making reasoned choices by applying only given criteria, providing actual marks for questions and having students provide a rationale for the given assessment of work, I ask students once a quarter to holistically reflect on their progress in the class (McDonald, 2003). Such reflection criteria helps students see their growth in content and as a member of a group. Excerpts of student reflections are shared below.

> "When other students asked me for help it reinforced my understanding because being able to teach something shows that you have the highest level of knowledge about it..."

> "This personal effectiveness activity really helped me see my strengths and weaknesses ... without this activity I don't think I would have been paying attention to how I was acting in my group..."

> "When our groups shifted and I no longer had super-smart K**** to lean on, I thought I didn't know how to do the work. But as soon as I was placed in a group with a more balanced skill level, I realized that somewhere along the way, I had learned how to do the work..."

Shifting to inquiry in class led to more engaged students, and higher quality and quantity of the work students completed. Average summative assessment scores increased five points. Absenteeism also decreased. Student questions, student-driven discussion and sharing of ideas also increased, indicating a positive impact on the classroom environment.

Student engagement and collaboration

A part of chemistry class is lab. Chemistry students attend two 38-minute lab periods twice every six days. The purpose is to give students an opportunity to learn experimental techniques, apply their knowledge of concepts learned in class, and to learn concepts that are specifically lab-focused. Labs are completely separate from class; lab sizes range from four to 14 students.

Given the nature of chemistry labs, this shift to inquiry-based learning was more precarious. Students need guidance on appropriate lab techniques. Traditionally, most inquiry-based chemistry labs focus on determining an unknown that has been pre-selected by the teacher. It is not common in a chemistry classroom to have students propose variables or conduct different experiments in the same class period. Given safety concerns and limited supplies, exploration within lab is often discouraged.

Sevian & Cacciatore (2009) stated the addition of one inquiry lab resulted in a statistical improvement, according to an ANOVA model on open-ended questions involving higher-order thinking skills (e.g., analysis, synthesis, and direct application) and the potential to improve student-to-student interaction. The ability to analyze data within a science lab leads students to a better

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Students work on a chemistry lab.

ability to process and determine the impact of the results of an experiment. The skills are essential so student can provide a rationale for their observations. Most changed labs occurred after the first quarter of the year based on how well students develop lab techniques and procedures and learn the content covered in class.

Initial exposure to guided-inquiry labs came from the "Imploding Can" demonstration-turned-experiment. (Kluiber, 2010). During this lab, a 12-ounce aluminum can is filled with 150 milliliters of water that is heated to boiling. As the can heats up, students share what they think will happen: "It will explode." "It is just going to cool down." Once evidence of boiling is present, the can is quickly inverted into a beaker of cold water and implodes. Students exclaim: "Whoa! Wow!" Students are asked what they would change about the initial experiment to impact the results. Students propose heating the water to a different temperature, using a different size can, adding more or less water, using salt or sugar water, putting more holes in the can.

After conducting the experiment, I noticed that more students posed questions about demonstrations. I began to record student "What if" questions about the demonstrations into a list of potential labs.

Following a luminol demonstration (two liquids are mixed and produce a glow), "What if" questions included:

- Does the length of tubing matter?
- What ratio of luminol to hydrogen peroxide is most ideal?
- Does the temperature matter?
- What if you add more …
- What about grinding up the chalk smaller?
- What about using a more concentrated HCl (hydrochloric acid)?"

Different questions on the same demonstration result in labs that are practical to set up, have enough variation to mitigate or resolve misconceptions, and offer varying challenges for students to explore.

The "Helper Sheet" gives students structure as they develop labs. To start the lab I demonstrate the procedure, emphasizing key pieces of the experiment and places from which students can build questions. This familiarizes students with experimental procedures and provides a forum to brainstorm alternatives and propose variables. This

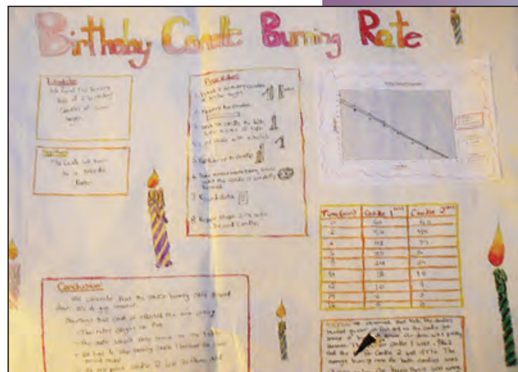
active engagement in changing just one small piece increases student comfort with the experiments (Putti, 2011), and facilitates buy-in. Students will guide each other — "Follow the directions in each box" — and, when probed about procedure development, indicate that they do not feel overwhelmed by the task.

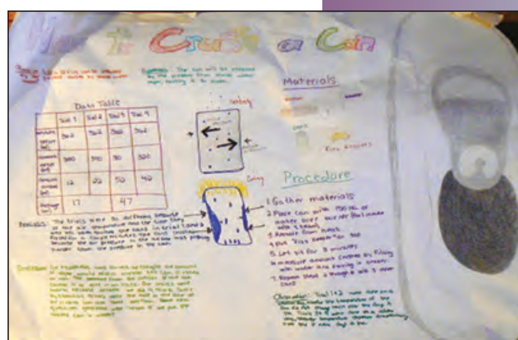
Groups then select one of the proposed variables and develop a procedure for their lab (Poock, Burke, Greenbowe, & Hand, 2007). Labs with a variety of rigor exist, as some questions are easier to approach than others.

Student-developed procedures are OK'd by me. This ensures students conduct safe experiments and allows for feedback or "hints" that helps them with procedures. Students then begin to conduct experiments, seamlessly modifying procedures as needed. The helper sheet allows me, at a glance, to gauge student progress.

Student groups align with one of two categories for assessing and reflection. Category One groups worked together to create a poster outlining their lab experience. The poster is student-graded, teacher-graded, and graded by another group.

In 90 percent of cases, the three grades fall within five points of each other and the average is taken. The student's self-assigned grades are most often the lowest, and they often say, "It is challenging to grade myself" or "Seeing others, I now know how I could have done better."





Sample student posters.

Students grading other students leads to an overall increase in the quality of the posters created. This happens, I believe, because students are aware of how articulate they need to be with their knowledge so other student-graders understand it. I also think students take pride when others comment on how great their work is. Students are not aware ahead of time who will evaluate their materials.

Category Two students write a thorough conclusion/analysis section in their Report Helper Sheet that is evaluated by the student and teacher. All students within a lab class engage in full class discussions following the laboratory experience. Students are provided with discussion guidelines. The written portions along with the discussions help students crystallize and articulate their knowledge in writing and orally.

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Student assessment of the lab helps students with increased critical-thinking capabilities, commitment to the course, and self-awareness of their own work. The results of the student lab assessments indicate higher average student scores on inquiry and guided-inquiry labs. Positive student feedback supports taking the additional time and effort needed for incorporating inquiry and guided-inquiry labs (see below) because the methods demonstrate a powerful impact on student learning. While the procedures are more straightforward and pre-written on the cookbook/verification labs (i.e., labs with clear directions, results that validate the introduction and questions that illicit already-learned content) in all other categories, the guided-inquiry and inquiry labs were more effective than the cookbook and unknown labs.

Conclusion

Shifting to student-centered, student-driven classes that utilize essential questions combined with POGIL activities and effectively formed groups has facilitated growth in rigorous content knowledge. It has also versed students in skills that are necessary in any profession students may pursue. The shift to inquiry lab activities has increased student engagement, interest and presence in labs.

As a result of the changes I made toward inquiry instruction, I can better meet students where they are with content. In class and lab, I can use student ideas and questions to give students appropriate activities or to help them build out their thoughts.

Students now exhibit an 81 percent Regents score average; a four-point increase with more than 40 percent mastery, and the skill sets essential for the 21st century workplace. These shifts also closely align with the up and coming Next Generation Science Standards. Following Regents Chemistry, 90 percent of the students continue to take a science class. This tells me I have become a supporter, not an enemy, of the education process for them, creating positive classroom dynamics that motivate students to attend. I will continue to develop purposeful classroom and lab activities to reach the ever-growing edges of the population I serve. Most importantly, students can see the progress they make and the value of their work. Plus, they like that they are able to provide insight and opinions for the future.

Student lab evaluation results

2012-2016 Student Lab Evaluation Results (158 female and 145 male)

	Target alignment	Interpret Data	Error Analysis	Future Ideas	Challenge	Procedure Execution	Interesting/Fun	Overall	Other
	average	average	average	average	average	average	average	average	
Cook-book (CB)	3.00	3.60	3.50	2.50	2.50	4.00	3.20	3.19	easy, OK, could definitely do
Unknown (Uk)	3.20	3.40	3.00	3.20	3.00	3.60	3.00	3.20	Ok
Guided Inquiry (GI)	4.20	4.00	3.80	3.20	4.60	3.50	3.20	3.79	Many questions; made sense in the end, LOVE the flame test!
Inquiry (I)	4.30	4.20	4.80	4.80	4.60	4.20	4.30	4.46	Really like this! Keep it! Great to do what we want!

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