After I changed my traditional high school chemistry labs (for sophomores and juniors) to inquiry labs (Backus 2005), my multiple-choice/short-answer finals no longer seemed to match the spirit and goals of the classroom. Inquiry lab days were filled with students collaborating, formulating plans, designing and carrying out experiments, and analyzing results as emphasized in the Next Generation Science Standards (NGSS). My traditional finals were not. Inquiry finals would provide an authentic problem setting (Gallagher-Bolos and Smithenry 2008) and act as a learning experience (Gupta 2016).

I discussed this disconnect between my traditional finals and inquiry lab final benefits with a colleague at an assessment seminar, and he encouraged me to make the change. The challenge was to develop an inquiry lab final that would be comprehensive of the semester, could be performed successfully, and could be completed in a reasonable time frame. This article describes the development process along with how the new finals met my student engagement and NGSS goals. Similar analysis could be applied to other disciplines.
Development of the first semester final

To begin, I examined our first semester, which contained four units: measurement, the atom, the periodic table, and bonding (metallic, ionic, and covalent including properties). These units had something in common: Students had identified unknowns in each of them. I decided this would be the theme for the final. For the unknowns, I chose two metals (Al and Zn), three ionic compounds (KBr, NaBr, and Na₂CO₃), one polar covalent compound (NH₂CONH₂), and one nonpolar covalent compound (C₂₅H₅₂).

To prepare for the final, students were told to review previous inquiry labs that involved identifying unknowns or distinguishing between types of materials. They were to bring a list of helpful tests from these labs and their lab notebooks to use as references. On the day of the lab final, the students received a handout that stated the problem: Match the seven given chemical samples that are marked with letters (A, B, C…) to their correct formulas (Al, NaBr, Zn, C₂₅H₅₂, Na₂CO₃, NH₂CONH₂, KBr) and classification (metal, ionic compound, polar covalent compound, nonpolar covalent compound). They were not given any procedures (see Handout for First Semester Final).

Student collaboration and formulating plans

After hearing the instructions, students gathered in their lab groups to collaborate. Students worked in assigned groups of four to save time. Typically, groups began by discussing their lists of tests: What tests should we choose? How will each test help us determine the unknowns? Should we use the test on every sample or just on some of the samples? Who will do each test? After the discussion, each group came up with its own plans. Students were required to have this plan before they started testing. For example, one group planned to do the following tests, sequence, and assignments:

One person would judge appearance (periodic table unit) to identify the two metals and then density (measurement unit) to distinguish between aluminum and zinc. The second student would do solubility in water to find the insoluble nonpolar compound, wax. The same student would measure conductivity in water (bonding unit) to distinguish between the three ionic compounds and the polar covalent compound, urea. The third person would perform flame tests (atom unit) to distinguish between potassium bromide and the two sodium ionic compounds. Finally, the fourth student would dissolve some sodium bromide and some sodium carbonate separately in water and react each with a magnesium nitrate solution (precipitation reaction from bonding unit). Only the sodium carbonate would form a precipitate.
Not all groups chose the same tests or sequence. For example, some used conductivity as a solid to identify the metals. Others used a brittleness test to find the nonpolar covalent compound. Still others chose reaction to acids and different precipitation reactions to distinguish between the ionic compounds.

**Designing and carrying out experiments**

After creating their plan, students designed and performed the experiments. For the design of their individual tests, each student answered questions for themselves: How much sample do I need? What equipment is necessary? Do I need additional chemicals?

If students needed extra supplies, equipment, or chemicals, they had to ask. I did not have any supplies out except their lab drawer glassware and the unknown chemicals. Having all supplies out is another option. I had appropriate materials such as balances, Bunsen burners, conductivity testers, flame test wands, and dropper bottles of various ionic solutions.

For safety, students were required to have their tests cleared with me before they began. For example, students wore required goggles and gloves, and students performing flame tests needed their hair tied back, no loose or dangling clothing or jewelry, a clear work area, and a beaker of water. They were also reminded of general Bunsen burner safety. Waste containers for the disposal of chemicals were also provided.

For previous labs, students typically recorded their information in a lab notebook including purpose, procedure, data, and analysis. To save time, students instead wrote their information on a provided blank data table and a blank calculations and results table. In addition to recording their own data, students shared, discussed, and recorded everyone’s data in the group. To keep students from hearing the identity or test results of Sample A from a nearby group, each group had different letters for their unknowns.

**Analyzing results**

After the students were done experimentally matching the unknowns to their chemical names and classification, they sat back at their desks and individually completed a conclusions and explanation table (see student example in Table 1). The table had four columns, with the first column listing each of the seven chemicals (Al, NaBr, Zn, C₅H₁₂, Na₂CO₃, NH₂CONH₂, KBr). Students filled in the rest of the table: The second column indicated the classification as metal, ionic compound, etc.; the third column was the letter ID (Which unknown was it?); and the fourth column included students’ experimental reasoning for their conclusions (e.g., What experiment/result showed it was an ionic compound, and what experiment/result revealed it was that particular ionic compound?). Having students write their own conclusions allowed me to assess individual understanding of the process. Students were graded on the following:

- Data table for completeness and accuracy (4 points)
- Calculations, for density, including significant figures (4 points)
- Correct classification as metal, ionic compound (1 point each – 7 total)
- Correct identification of unknown, A, B, C, etc. (1 point each – 7 total)
- Reasoning – what experiment/results proved it was a metal (2 points each – 14 total)
- What experiment/results proved it was this metal, Al and not Zn (2 point each – 14 total)

Additionally, teachers could assess more aspects of the inquiry process, such as collaboration and planning (Barton et al. 2006; Donaldson and Odom 2001).

**TABLE 1**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Type of material/compound</th>
<th>ID</th>
<th>Reasons/tests that support identification. Must include minimum of 2 tests used. Must include how you experimentally determined it was ionic, metallic, polar covalent or nonpolar covalent, and how you eliminated the other possibilities–how did you narrow it down to this answer? (For example: It was an ionic compound because ... And it is this ionic compound because ....)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Metal</td>
<td>B</td>
<td>Sample B is a metal because it conducts electricity as a solid. It is Al and not Zn because we determined its density was 2.85 g/ml, which is closer to Al (2.70 g/ml) than Zn (7.13 g/ml).</td>
</tr>
<tr>
<td>NaBr</td>
<td>Ionic Compound</td>
<td>A</td>
<td>Sample A is an ionic compound because it conducted electricity when dissolved in water. It is this ionic compound, NaBr, and not KBr because it produced a yellow flame test and not a violet one. It is NaBr and not Na₂CO₃ because when dissolved in water, it did not react with Mg(NO₃)₂. Na₂CO₃ would have reacted. (Note: Students could have chosen a variety of chemicals to distinguish between these two ionic compounds.)</td>
</tr>
</tbody>
</table>
Goals reached
I met my goals and students were successful because most groups identified all seven chemicals correctly. More importantly, students collaborated, formulated plans, designed and carried out experiments, and analyzed results. For example, instead of a multiple-choice question on attributes of materials, students discussed various properties, chose the most helpful tests, performed those tests, and understood the results. I occasionally stopped the class during the final and exclaimed, “Can you feel the chemistry?!” The room was filled with activity!

Additionally, the final contained concepts from all the units and was completed in the time allowed (an extended lab period of about 100 minutes). This final could also be altered to fit into a smaller time frame, if needed. For example, students could perform tests on one day and write conclusions on another day. Alternatively, students could be given the same possible list of seven chemicals for their unknowns but only four or five actual samples to identify.

Development of the second semester final
Designing the second semester final was a bigger challenge. Our units involved organic chemistry, stoichiometry, thermodynamics, gases, and acids/bases. I was initially stumped. What could I do that would involve all these topics? Once again, I was inspired by some colleagues. For the gas unit, students analyzed a commercial toy, called a bomb bag. The toy consists of an outer sealed bag that contains powdered sodium bicarbonate and a smaller inner container with a citric acid solution. When the strong outer bag is squeezed, the inner container is broken. The citric acid solution then mixes with the sodium bicarbonate solid producing carbon dioxide gas. The gas causes the outer bag to expand until it pops with a loud noise. When I thought about the toy, it involved all of the second semester topics! Citric acid is an organic compound. One of the two chemicals (citric acid or sodium bicarbonate) was the limiting reagent. The chemical reaction between the two was endothermic. The product is a gas, and the two chemicals are an acid and a base! Perfect!

For the final, I wrote a letter to the students from Sy N. Tist, a toy manufacturer, who wanted to make and sell his own commercial bomb bag version. He needed help analyzing some prototypes/mock-ups. At the beginning of class, I conducted a demonstration of the commercial bomb bag. Each pair of students would then analyze a unique prototype and answer questions from Sy (see Figure 1). The prototypes (labeled A, B, C, etc.) were snack-size zipper plastic baggies containing varying amounts of sodium bicarbonate (5.2 g to 12 g) and a 10 ml vial filled with varying concentrations of a citric acid solution (1.2 M to 2.2 M). I found accordion-style vials that would pop open when squeezed, but any vial with an easily removable lid could work (Figure 2). As in the first semester final, students were allowed to use their lab notebooks for reference. Purpose, procedures, and data were recorded in their lab notebooks for this final. To save time, students received a calculations and results table that included each of Sy’s questions in the first column and a second blank column for their answers.

Student engagement
As with the first semester final, students had no procedures, just a challenge. This time the challenge was to answer all of Sy’s questions (Figure 1). Working in pairs, students started by discussing the questions and determining a plan. Since there were so many questions, I encouraged students to answer them in order and plan as they went along. For each question, students collaborated before deciding what to do. Some questions needed experimental answers, others did not. As before, if the answer involved an experiment, students determined their own procedures. This included deciding the equipment, chemicals, and quantities to use. If they needed chemicals or supplies, they had to ask me. As before, I had the necessary supplies available, including pH paper, burets, 3.0 M NaOH for titration, phenolphthalein, balances, large graduated cylinders, Styrofoam cups for calorimeters, thermometers, solid sodium bicarbonate, citric acid solutions, and snack-size zipper plastic baggies.

For safety, procedures needed to be cleared with me first. For example, if students chose to titrate to determine the concentration of the citric acid solution (one of the questions), students wore goggles and gloves and were reminded that acids and bases are caustic to the skin. They needed to wash their skin if there was a spill and inform me immediately. After each experiment, they analyzed the results and placed answers on the handout.

FIGURE 2
Picture of a prototype: A zipper snack-size baggie with sodium bicarbonate and two different possible vial types with citric acid solution.
Questions from Sy N. Tyst and point value

1. What letter or number mock-up do you have? (1 point)

2. How much solid (in grams) and how much liquid (in ml) are present in your mock-up? (1 point)

3. We sent solid sodium bicarbonate and solid citric acid (H$_3$C$_6$H$_5$O$_7$) to the company we hired to make the bomb bags. They were supposed to dissolve the citric acid in water and place in the vial and leave the sodium bicarbonate as the solid. Determine which scenario is true: (A) The solution in the vial is citric acid in water. The solid is sodium bicarbonate, or (B) The solution in the vial is sodium bicarbonate and water. The solid is citric acid. How do you know? (2 points)

4. Citric acid is the common name for 2-hydroxypropane-1,2,3-tricarboxylic acid. How does this name fit the molecule? Please explain by labeling a drawing. (Hydroxy is another name for an OH group). (3 points)

5. Experimentally determine the concentration of the solution in the vial in moles per liter, citric acid, H$_3$C$_6$H$_5$O$_7$, has 3 active H$^+$’s (nH$^+$ = 3). (3 points)

6. How acidic is the solution? Please experimentally determine the pH. What is it? How do you know? (1 point)

7. Determine the H$^+$ and pH mathematically (so we can include in our safety statement about the toy). Assume the H$^+$ and pH is primarily due to the first of the 3 H’s dissociating. You need to use the molarity from question 5 as the initial concentration. (3 points)

\[ \text{H}_3\text{C}_6\text{H}_5\text{O}_7 \leftrightarrow \text{H}^+ + \text{H}_2\text{C}_6\text{H}_5\text{O}_7^- \quad \text{K}_a = 7.1 \times 10^{-4} \]

8. We noticed that the bomb bag gets cold when the reaction occurs. We may want to use the chemicals to make a cold pack. How many joules of energy are absorbed when a whole bag reacts? Please experimentally determine the joules/bag contents. (3 points) You must react one full bag with one full vial (DO NOT SEAL THE BAG for this reaction.)

9. When the sodium bicarbonate reacts with citric acid, H$_3$C$_6$H$_5$O$_7$, it produces carbon dioxide, water, and sodium citrate (Na$_3$C$_6$H$_5$O$_7$). What is the balanced equation for this reaction? (2 points)

10. If the entire amount of grams of solid reacted in your bag, how many moles of carbon dioxide gas would form? Please determine mathematically. (3 points)

11. If all of the liquid reacted, how many moles of gas would form? Please determine mathematically. You must use the volume and molarity to determine this. (3 points)

12. Which will limit the reaction, the amount of solid or liquid? Which is in excess? (We may want to cut back to save money.) (1 point)

13. How much of the one in excess is actually used? (1 point)

14. How much of the one in excess is left over (remaining)? (3 points)

15. Based on your answers to 10 and 11, how many moles of gas will form? (1 point)

16. What is the volume of the baggie in liters if it fills up all the way? (1 point)

17. If the number of moles of gas from question 15 fills the baggie totally full without breaking, what is the pressure that would build up in the bag? Please determine mathematically. (3 points)

18. Based on your pressure, should your bomb bag work (pop)? Why? Show your teacher! (1 point)

19. When tested, did it pop? Don’t try popping until you get your teacher. (1 point)

20. What are two more things you would advise testing for, if you had more mock-ups? (1 point)

21. How confident are you in the above answers? Explain two possible sources of error, if you did everything well (not human error or error due to instruments). How would the errors affect your results? (little/lot and high/low) (2 points)
Summary of second semester final
During the final, students ended up doing a variety of activities. Students

• determined the pH of the solution experimentally and mathematically,
• calculated the concentration of the citric acid solution using titration,
• measured the joules absorbed from the reaction using calorimetry,
• mathematically determined which chemical was the limiting reactant,
• calculated the theoretical pressure that the gas would form in the baggie,
• decided if this gas pressure would cause the bag to pop, and
• tested their prototype!

Before testing their bomb bags, the students had to show me their reasoning and results. To pop the bags, the students obtained a vial filled with their citric acid solution and refilled their baggies with the appropriate amount of sodium bicarbonate. Students placed the stoppered vial in the baggie and made sure the baggie was completely sealed. They then squeezed the accordion vial (or alternatively removed the stopper) to mix the chemicals and quickly dropped the baggie in a plastic tray (or a sink) and waited for the pop! They were so excited when it worked! I made sure that all of the prototypes contained sufficient chemicals to cause a pop so that the students would be excited even though I had warned them that some may not. (See the Responses for Second Semester Inquiry-Based Lab Finals handout summarizing the questions and student responses).

Since there were many tests to perform throughout this final, students were allowed to refill their baggie with the correct amount of sodium bicarbonate (based on original measurements). I also refilled their vials with the correct concentration of citric acid based on their prototype letter, as needed. For this final, I allotted a full five days of testing, which included two lab periods (88 minutes). I did not allow students to take home their question packets or lab notebooks. They were required to do both the experiments and calculations in class. To allow for the five class days needed, I skipped the review days that I had often set aside at the end of the semester in favor of doing a more authentic inquiry final. Students were graded on answers to the 21 questions (40 points total, as listed in Figure 1) and their lab notebooks (10 points).

Conclusion
I was very pleased with both the first and second semester results. The only concerns I had were the increase in grading time and that the assessment was more group oriented rather than individual. I accepted the extra grading time as worth it, and for the individual assessment issue, I was satisfied that the first semester had an individual writing component. For the second semester, I also formed the lab groups according to similar ability. Overall, the finals achieved my goals: They involved students collaborating, formulating plans, designing and carrying out experiments, and analyzing results. The finals also involved topics from the entire semester, they were completed in the time allotted, and students were successful! The finals were some of the most exciting class days! Imagine that!

Safety notes
It is important to follow standard safety procedures and disposal regulations. This article is not intended to cover all the safety requirements for the activities. Please consult references such as MSDS sheets, state requirements, and reliable reference materials. Students should be aware of proper safety rules including use of Bunsen burners, acids, bases, and all chemicals used. Goggles must be worn at all times in the lab. Please consult NSTA Lab Safety guidelines at www.nsta.org/topics/safety#tab

ONLINE CONNECTIONS
Handout for second semester final: https://bit.ly/40d51YM
Responses for second semester final: https://bit.ly/3Jx2Acr

REFERENCES

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