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ABSTRACT

High school conceptual chemistry students engaged in daily estimation activities and frequent in-class graphing to practice mathematical reasoning, argumentation, and visual analysis. Students applied those skills by regularly creating and analyzing graphs using both real-world and lab-generated data sets. Self-confidence surveys, performance assessments, and presentations were used as data collection instruments. Data were processed using quantitative and qualitative analysis strategies. The results suggested that students improved their abilities to create and interpret graphs using mathematical reasoning and visual analysis, key components of critical thinking. Interview data suggests no overall change in student attitude towards the utility of graphs as a means of conveying information.
INTRODUCTION AND BACKGROUND

Project Background

Graphs are all around us – from advertising, to news reports, to health care claims. Individuals must be able to critically interpret advertisements to avoid falling for embellished claims, they must understand the trends or scales shown in news reports to spot bias or misleading statements, and they must be able to understand spreads or distributions to analyze where they fall on a chart of a health metric. Moreover, “a scientifically literate individual should be able to make sense of both [graphical representations and natural language] in relation to one another,” write Whitacre and Saul in a 2016 journal article on interpreting scientific graphs. While all individuals in a 21st century society need the skills to analyze and describe graphs, the critical thinking required for graphical analysis is especially important for scientifically literate high school individuals.

For students, Lai, Cabrera, Vitale, Madhok, and Tinker emphasize the importance of “interpreting and creating graphs… in scientific practice.” They point out that the K-12 Next Generation Science Standards call for students to use graphs “for scientific modeling, reasoning, and communication.” Taken together, the modern-day importance of students successfully creating accurate and informative graphs, and of students successfully drawing information from complex graphs, is obvious and of critical importance. Another stated goal of NGSS is career readiness, and both graphical analysis and critical thinking are critical to a wide variety of vocations. Statisticians, weathermen, medical researchers, and actuaries are examples of careers in which graphs are used
daily. Advertisers and political pollsters move beyond presenting data and utilize graphs to sway opinion or push a product. The Bureau of Labor Statistics predicts a growth in STEM-related fields of over 9 million jobs between 2012 and 2022, meaning those students with superior graphical analysis and critical thinking skills will be better prepared to meet this growing need.

At the same time graphing skills are becoming more important to students, the students at my school show some deficiencies in their fluency with graphs. Specifically, students have struggled in past courses to create graphs that accurately show trends in the data, they struggle to interpret complex information depicted by graphs, and they have limited experience with statistical analysis to accurately project or extrapolate perceived trends in the graph. Taken together, for my AR project, I was interested in exploring methods of improving those skills.

General chemistry students range from being skilled in laboratory techniques and equipment usage to never having been in a laboratory setting. Beyond the anecdotal evidence of this in my classes, Padgett and MacGowan (2013) provide several citations to back up this assertion and go on to provide a theoretical framework for the value of graphing for all these students, citing references for each statement. They begin, “To use graphical data correctly, students must utilize cognitive memory, convergent thinking, and evaluative” and continue by saying that, “graphing not only employs and fosters higher-order thinking skills, it also helps students develop problem-solving strategies.” This concise and well-referenced introduction provides echoes the inspiration for my
project. In my own classroom, I hoped to utilize real-world graphing and daily estimation activities to help students achieve those skills.

**Teaching and Classroom Environment**

I focused my AR project on my Chemistry in the Community (ChemCom) class. ChemCom is a conceptual chemistry course with very little math. In place of math, the class devotes time to real-world connections, class discussions, and projects. The students in this class tend to struggle with math, with the NGSS Science and Engineering Practices of “Developing and Using Models”, “Analyzing and Interpreting Data”, Using Mathematics and Computational Thinking”, and “Engaging in Argument from Evidence”, and with "student skills" in general, such as organization, motivation, and follow-through. One overlapping application of these four practices that my students are particularly weak in is graph creation and interpretation. Students have a difficult time converting data between tables, graphical representations, and narrative forms. As written above, in addition to the value in chemistry and other science classes, this skill has real-world applications ranging from economics to advertising to weather. Beyond gaining chemistry-specific content knowledge, helping students to achieve scientific literacy is a stated goal of my science courses.

Chemistry in the Community is generally a 10th and 11th grade course of 10-15 students at Williston Northampton. Williston is a co-educational boarding school in Western Massachusetts of ~450 boarding and day students from diverse socio-economic, cultural, and regional backgrounds, and who demonstrate a wide spectrum of academic ability. Williston enrolls approximately 17% students of color and 21% international
students, with 43% of students receiving some form of financial aid. ChemCom students are representative of this diversity, though more-so than their peers, they tend to have historically struggled in school, and especially in math and science. Whereas their peers are able to reason abstractly, many ChemCom students struggle with abstract concepts, algebraic manipulations, and multi-step problems. This is often a terminal chemistry course for them, though it does prepare students for grade-level biology. Due to the limited formal science courses a student may take beyond ChemCom, ingraining a lasting scientific literacy becomes even more pertinent.

As the sole teacher of Chemistry in the Community, I had great flexibility with the curriculum, content to cover, and eventual end of the course. As such, I was confident in being able to spend time working on graphs and graphing without needing to keep stride with a colleague in terms of content such that we arrived at the same end point for the course. The 10 students in the course this year provided a small sample size, but still large enough to yield meaningful results and allow for a deeper dive into qualitative data.

**Focus Questions**

Having identified the deficiencies in my students both in the general terms of the Science and Engineering Practices, and more specifically, in terms of their abilities to generate and analyze mathematical graphs, I then needed to devise a main research question and sub-questions to study. The value of number sense activities and real-world data appeared repeatedly in the literature, and thus my main research question was written to focus on those two activities as strategies to improve graphing and, more generally, critical thinking. The background research done for the Conceptual Framework
provided four interesting aspects of graphing that allowed me to divide the main research question into sub-questions: graphing to communicate reasoning, the value of real-world and place-based graphing, advantages of Excel over graphing by hand, and the effect of number sense activities. For the Action Research project, I designed activities and instruments to measure student progress on the four sub-questions, which would combine to then address the central question. The main research question and sub-questions are below.

**Research Question:**
- How effective are estimation and real-world graphing as strategies for promoting high school students’ skills with graph creation, interpretation, and critical thinking?

**Sub-questions:**
- Will requiring students to use graphs to model scientific phenomena and communicate their reasoning increase their self-efficacy?

- Is graphing real-world or place-based (that is, information unique to my students’ situations) data effective at encouraging them to think more about the meaning of graphs and appreciate the significance of graphing data?

- Do students show improved graphing ability and interest when using Excel over graphing by hand?

- Will daily visual exercises in number sense (ie Estimation180 and Graphing Stories) improve students comfort with data and graphing?
Taken together, the focus question and sub questions provide a wide-ranging approach for ascertaining and hopefully improving students’ abilities to think critically and to analyze graphical representations of data that they encounter in both the classroom and the real world. Again, these skills would have benefits both during and then lasting well beyond their time in Chemistry in the Community.

CONCEPTUAL FRAMEWORK

Compared with traditional chemistry courses, the overall goal of Chemistry in the Community is less to prepare students for future advanced chemistry courses, and more to develop their student skills while building a working appreciation for science and chemistry in their everyday lives. As such, the research questions focused more on graphical literacy, real-world data, working with technology, self-confidence, and number sense than with specific chemistry content. Certainly, improving in those areas would help students to become better chemists, but I was most interested in them becoming better students and critical thinkers first. Using this goal as a basis for my conceptual framework research, I explored articles from the literature relating to the importance of graphical literacy in school and society, specific techniques to foster graphical literacy, and tools to measure changes in students’ graphical literacy. These papers laid the groundwork for a multi-pronged approach to improving graph creation and graph analysis, as well as building a general appreciation for the value of graphs, over the course of the Action Research study.

For the purposes of consistency throughout this study and paper, I used the following definitions for three key objectives. Self-confidence: student perception of their
ability with a specific task and comfort with doing this particular task. This would be assessed on a Likert scale. Graphical literacy was defined as the ability to create an accurate graph from data, to analyze a graph through discussion of trends, slope, and/or extrapolation. In the study, I would rank student work on a rubric ranging from Excellent down to Poor, and translate those rankings into numeric scores. Finally, scientific literacy is defined more broadly as an understanding of the scientific phenomena that impact our daily lives, or understanding cause and effect. Cause and effect is the second NGSS cross-cutting concept, and is perhaps most relevant for this population of students as they try to connect scientific phenomenon (cause) to their everyday lives (effect).

The Importance of Graphical Literacy

In an era where scientific data is often interpreted or politicized based on ‘beliefs’ rather than facts, the accurate analysis and interpretation of graphs remains a crucial component of critical thinking, visual literacy, and responsible citizenship. An Atlas Obscura article titled “The Scottish Scoundrel Who Changed How We See Data” (Giaimo, 2006) provides a colorful backstory to modern arguments about the value of graphing. Giaimo begins by describing how historically, audiences were accustomed to reading or listening to rhetoric, writing succinctly that it was, “Well-written arguments [that] would get educated people on your side.” He continued by describing the slightly negative view in which graphs were held at the time, “illustrations were thought of as inaccurate “trifles,” suited more for working through arguments than for presenting them.” Perhaps one reason for this was that those who were making the graphs lacked the artistic skill needed for publication, creating another barrier to the introduction of graphs
as compelling narrative or influencing tools. The “Scottish Scoundrel” referenced in the article’s title is William Playfair, an 18th century Scotsman, who “singlehandedly popularized the theoretical plotting of data to reveal suggestive patterns – an achievement that foretold the graphic explosion of the nineteenth century” (Wainer, 2005). Now, far from their origins as “trifles,” informative and attractive graphs of all types are consistently found in print and digital media supplementing or even supplanting conventional rhetoric in conveying mathematical information to readers in all areas of academics and national/international news coverage.

In their article “Instructional Strategies to Develop Graphing Skills in the College Science Classroom,” Harsh and Schmitt-Harsh summarize this transition from pre-Playfair rhetoric to modern graphical information when they quote the American Association for the Advancement of Science, saying, “proficiency in graphing is considered a central element of scientific literacy, given the importance of succinctly communicating complex information.” They go on to quote the National Science Board, which stresses the value of graphing as “even more evident when considering that television and the Internet… commonly present visual data that inform opinion on public policy and personal actions.” Furthermore, in *Graphic discovery: A trout in the milk and other visual adventures*, author Howard Wainer (2005) references weather forecasts, the Dow Jones average, and other modern applications when arguing why students should know how to graph and read graphs correctly. The analysis and logical thinking involved in graphing develops and sharpens students’ critical thinking skills and their ability to conceptualize numeric data in meaningful ways. That is, a proficiency in reading and
interpreting graphs creates more informed consumers, more scientifically literate citizens, and more influential change-makers.

**Techniques to Foster Graphic Literacy and Self-Efficacy**

Gaining proficiency in any area takes consistent practice. One aspect of teaching Chemistry in the Community involves convincing students that they are capable of succeeding in the course, and in school in general, if they put particular skills into practice. For example, I require the students to bring specific, thoughtful questions to review sessions in order to show the progress they have made so far, rather than allowing them to simply ask for extra help with all of the material. Still, they often fall into the habit of wanting me to tell them the answers, or they want to memorize information but then struggle to explain the deeper connections between concepts on free response assessment items. That is, they are often operating on the first two levels of Bloom’s Taxonomy (Knowledge and Comprehension, respectively) and need focused work to progress to Application, Analysis, Synthesis, and eventually, Evaluation. Based on my experience with teaching and reinforcing these best practices for student success, I knew my AR project would require consistent practice as part of the process in order to achieve successful results with this population of students.

This can be summarized as improving their epistemic beliefs – that is, improving the students’ perceived confidence in the subject area must first start with their beliefs about the subject in general. Chemistry, like math, has a daunting and stuffy reputation stemming from the drill-based courses of yesteryear, and too often students buy into this outdated narrative because of portrayals in the media or stories from their parents. Rather,
a modern chemistry course like Chemistry in the Community is an investigative way of learning about the ways in which chemistry impacts our daily life, from water quality to air pollution to soil fertilization. Graphs, and quality graph interpretation, in place of the perceived need to memorize masses and charges on the periodic table, represent the crucial kinds of skills needed for success in this course.

The need for consistent practice was confirmed by Roth and McGinn, writing in a 1997 Science Education journal article about whether graphing is a cognitive ability or an acquired skill. Their results show that it is more of the latter, describing scientific graphing as “observable practices employed to achieve specific goals.” Therefore, I developed a series of assignments and daily practices that provided concrete, observable objectives in graphing. Using daily exercises from Estimation180.com (sample exercises are found in Figures 1 + 2 in the Methodology section), I asked my students to practice their visual analysis with thoughtful, logical, and well-supported reasoning every day. I incorporated more graphing lessons and assignments in the course this year than I ever have before and asked students, individually and as a class, to revisit and rework particular graphing assignments. This consistent practice of reasoning in Estimation 180, combined with a variety of graphing tasks, developed a common language around graphing and increased the students’ familiarity with this type of thinking and data analysis.

Having a one-to-one Microsoft Surface program at Williston makes technology a natural and integral part of all of our classes. Using computer-aided graphical data analysis to teach the design and interpretation of graphs is one of the best means of
exposing students to the NGSS Science & Engineering practices, especially those of modeling, investigating, and analyzing data, and then communicating that information. However, students often are only taught the low-level mechanics of constructing a single kind of graph when given a table of information, and not these analysis skills (Jackson, Edwards, and Berger, 1993). In that paper, the authors investigate the efficacy of using a computer to eliminate the drudgery of plotting and how the time saved allows for higher level thinking about the design and interpretation of graphs. Based on our daily use of the Surfaces, it was natural to move away from graph paper and onto Excel, where I demonstrated for my classes how to create a variety of graphs based on a data set and then asked them to replicate the process using all of the required components of a graph in an accurate manner.

All of these methods—consistent practice, modeling, technology integration, real-world data, and collaboration as a class—are supported by Harsh and Schmitt-Harsh in their article “Instructional Strategies to Develop Graphing Skills in the College Science Classroom.” The authors focus on five different strategies for advancing graphing ability. The five methods are shown in Table 1 below.

Table 1

*Instructional Strategies to Develop Graphing Skills in the College Science Classroom*

<table>
<thead>
<tr>
<th>Design Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Collection of Authentic Data</td>
<td>Students should be active participants in authentic scientific investigations of realistic and contextualized problems.</td>
</tr>
<tr>
<td>2. Exposure to Complex Data</td>
<td>Students should be exposed to, and encouraged to engage with, complex data sets that reflect the genuine nature of research.</td>
</tr>
<tr>
<td>3. Two-step Data Analysis Approach</td>
<td>Development of graphing skills should proceed using a two-step design that first engages students’ cognitive processes and then uses technology for visualization purposes.</td>
</tr>
</tbody>
</table>
Explicit Graphing Instruction

Students’ proficiency gaps should be attended to by using explicit teaching instruction or “modeling” of graph skills.

Collaborative Graphic Practices

Students should work collaboratively to make sense of and effectively communicate data.

Methods to Study Graphic Literacy

Also related to technology integration, one capstone project in particular from the MSSE library provided an excellent sample methodology that I studied and adapted for my AR project. O’Leary (2015) wrote about “the effectiveness of TinkerPlots software on student's ability to analyze data.” The project showed that “students' ability to analyze data increased and their attitudes improved when analyzing data. Data also indicated that teacher's attitudes improved when teaching data analysis.” Here, there was a specific treatment given (Tinkerplots) to affect change. After reading O’Leary’s paper, I was inspired to use Graphing Stories (See Figures 3 + 4 in the Methodology section below) as a graphing application in my project.

In a paper in the journal School Science and Mathematics, Brasell and Rowe investigated graphing skills among high school physics students. The authors noted that despite a recent (as of 1993) increase in interest in the kinds of problems students encounter with graphs, “there is a relative paucity of research pinpointing specifically how and why students have problems with specific tasks.” Getting at the “how and why” allows treatments to be designed with those gaps in understanding in mind. Specifically, the paper’s authors found that students’ abilities to interpret events on a graph depend on the direction of translation and on the type of verbal description used.
Techniques to Measure Changes in Students’ Graphical Literacy

In their widely cited article, “An investigation of the relationship between logical thinking structures and the ability to construct and interpret line graphs,” Berg and Philips (1994) studied the relationship between logical thinking structures and the ability to construct and interpret line graphs. Specifically, they looked at the logical progression of subjects from 7th, to 9th, to 11th grade, and the corresponding ability to work with graphs. The students in my Chemistry in the Community class are generally 10th and 11th graders, yet they often perform several grade levels behind their peers in math and science. Thus, they are biologically at the upper end of Berg and Philip’s study, but academically nearer to the beginning. With this in mind, I was curious to see how my students would fare on initial formative assessments and then how they would perform after a series of treatments. Formative assessment is something that I have studied but have failed to implement in the classroom. Rather, we tend to begin new material and work our way toward a mid-chapter quiz and an end-of-chapter test. With this graphing project, I had my students complete the first performance task without prior discussion of graphing so that the first task could serve as a baseline from which to measure growth. In addition to my prior understanding of formative assessment, I was inspired to begin with this baseline performance task by Padgett and MacGowan (2013) who present a “meaningful laboratory exercise for introductory or general chemistry students to perform, especially on the first day of class.” Specifically, their protocol focuses on “graphing… data analysis, [and] good laboratory note-taking.” Likewise, I required my students to practice a variety of graphing skills throughout subsequent graphing assignments and labs, and I
had them repeat one assignment with slightly more specific directions when I was not satisfied with the level of detail or analysis in their explanations.

METHODOLOGY

Introduction

While graphing skills are becoming more important to interpreting and evaluating everyday life, students’ fluency with graphs in this course have historically show some deficiencies. Students have struggled to create graphs that accurately show trends in the data, they have struggled to interpret the information presented by graphs, and they have limited experience with mathematically quantifying trends in the graph. For my AR project, I was interested in improving students’ proficiency in these areas, with the overall goal of improving their analytical and critical thinking skills in both chemistry class and in broader applications. These parameters led to the research question and sub-questions stated below in Table 2.

Table 2
Research Question and Data Collection Triangulation Matrix

| Research Question: How effective are estimation and real-world graphing as strategies for promoting high school students’ skills with graph creation, interpretation, and critical thinking? |
|---|---|---|
| Sub-questions | Data Collection Instruments | Rationale |
| Research SQ. 1: Will requiring students to use graphs to model scientific phenomena and communicate their reasoning increase their self-efficacy? | • Performance assessment | The benefit of frequent practice in graphing (ie during labs) will be apparent in a positive trend in performance assessment scores. Self-confidence surveys and interviews will capture students’ qualitative feelings on graphing. |
| | • Self-confidence survey | |
| | • Interviews | |
### Research SQ. 2: Is graphing real-world scenarios or data effective at encouraging them to think more about the meaning of graphs and appreciate the significance of graphing data?

- Performance assessment
- Short written quizzes
- Interviews

**Periodic performance assessments will track the progress students are making. Quizzes can probe their understanding of several prepared graphs. Interviews will help to make the connection between the real-world graphing and their general understanding.**

### Research SQ. 3: Do students show improved graphing ability and interest when using Excel over graphing by hand?

- Self-confidence survey
- Interviews

**Interviews and administered surveys will gather data about what students found most effective after several rounds of graphing by hand and graphing on Excel.**

### Research SQ. 4: Will daily visual exercises in number sense (ie Estimation180 and VisualPatterns) improve students comfort with data and graphing and explaining their reasoning?

- Formative and summative assessments
- Interviews

**Practice with Estimation180 and VisualPatterns, followed by graphing assessments will probe student understanding to determine if those exercises helped them think quantitatively.**

Several specific sub-questions arose from my class and the goal of my Action Research. For the first sub-question, I administered regular performance tasks to the students to measure their self-efficacy with graphing data and extracting data from graphs. I used a combination of lab data and data gathered from online sources not related to the course. In this manner, students saw and graphed data from a familiar chemistry context, but also needed to establish relationships or trends from unfamiliar data. My hope here was that with frequent exposure to familiar and unfamiliar data – whether it was in table, graphical, or narrative form, that students would become more adept at finding ways to express that information and discuss observed trends.
While experimenting with various methodologies throughout this AR project, I asked students to complete “Confidence Surveys” to self-assess their ability in the areas of graphing we had practiced or would be practicing next. As this population of students is sometimes trying to just “get by” in their courses, I thought emphasizing some metacognition was an important aspect of building critical thinking skills and becoming invested in the process of developing stronger graphing abilities. Follow-up surveys gave valuable qualitative insight that was combined with the quantitative output to paint a more complete picture of their experience and self-efficacy.

To answer the second sub-question, I also utilized performance assessments to probe student understanding. For this sub-question, I gathered scientific real-world data and data from our school community for the students to graph. Examples of this included pond water data and atmospheric data. The Chemistry in the Community curriculum asks students to think about and graph these same data points, but by utilizing information closer to home, my hope was that students would buy in to a greater extent. As before, I surveyed my students about their experience with the graphing, and about whether or not place-based graphing is helpful.

Considering the work of Brasell and Rowe on the difficulty of why students struggle with graphing, I asked students to analyze graphs from a variety of sources – including graphs they found in the news on their own – and to work through explaining the graphs in writing and in class discussion or presentations. The public aspect of these explanations required students to own their analysis in a way that differs from answering questions on paper. Likewise, completing the confidence surveys required them to own
their learning and to be prepared for the next graphing challenge. As a result, I incorporated more graphing tasks and a wider variety of graphing lessons in Chemistry in the Community than ever before and monitored the students’ progress throughout the process of engaging in graphing. Using consistency and repetition as the cornerstone of this practice, I made graphing become a regular part of our chemistry studies and required students to further develop their visual and scientific literacy through these methods.

To measure my students’ growth in graphing creation and analysis, I assigned point values, representing the quality/success of their work, to performance tasks and analyzed the resulting scores. Additionally, I interviewed my students to gather their input on their growth (again asking them to take ownership of their thinking and learning) and compared their answers on their confidence surveys to the results of their performance tasks. Taken together, I gathered a clearer picture of how my extra attention to graphing this year benefited their learning, as well as where there is more room for improvement. In a course where “student skills” are as important as the content itself, the methods for teaching and assessing graphing that were part of my project provided a framework for consistently practicing critical thinking, logical analysis, and scientific literacy in ways that move students beyond memorized answers and other passive learning methods.

For the fourth sub-question, similar to O’Leary’s goals with Tinkerplots, I wanted to see if Graphing Stories could provide real-world data sets for students to graph as well as a consistent method of graphing practice to employ in class. I also hoped Graphing
Stories would promote increased student engagement in the graphing process, which could then carry over to other graphing work.

**Treatment**

Through a series of early formative assessments, I established where my students were in their abilities to create simple scatter plot graphs of the relationship between two variables. Likewise, I assessed their ability to correctly draw information from a variety of complex and unfamiliar graphs. After that, I ran a number of graphing-specific lessons throughout the year as specific treatments. To gather results, I used a combination of performance assessments and surveys, as well as interviews to follow up as needed and compared against the earlier results. In units on the atmosphere and pollution, I had my students taking quantitative measurements of time, temperature, and ozone (from NOAA.org) and looking for connections between those. Also during the treatment units, I began class each period with a visual quantitative reasoning exercise. This included a combination of Estimation180 (adapted from [www.Estimation180.com](http://www.Estimation180.com)) and Graphing Stories (adapted from [www.graphingstories.com](http://www.graphingstories.com)). In the first, students are presented with an image or video and need to make an estimate and then defend that estimate with mathematical reasoning (Figures 1 and 2 below). In the second, they watch quick videos and then attempt to graph the action (Figures 3 and 4 below). In both cases, students were tasked with working on their quantitative reasoning and the connection between numbers and visual information.
Figure 1. Students are asked to estimate the number of candy corns in the bag and to defend their reasoning with math. The previous activity was estimating the number in the small cup.

Figure 2. Students need to defend an estimate for the percentage of the pie eat. Also valuable was establishing “an estimate you know is too high” and “an estimate you know is too low” to establish bounds or limits to make a reasonable estimate from.

Figures 3+4. Two examples from Graphing Stories. In the first, students graph water volume over time (continuous rate). In the second, they graph the height of the bar (near sinusoidal). In both instances, students must scale and label axes, as well as identify discrete points to graph.
The real-world graphing and daily warm-ups represent the treatment for my Action Research study. To provide a baseline for student graphing ability, and to give students an opportunity to work on their graphing, I emphasized frequent graphing of lab data during the middle two units of Chemistry in the Community: the atmosphere and water. Gas laws and solution chemistry presented many opportunities for graphing practice stemming from labs. In addition to making several graphs per lab during this time, I had students make several kinds of graphs, and tailored the labs accordingly. For example, in a gas laws lab, students graphed pressure versus volume, volume versus temperature, etc. My hope was that when the students repeatedly generated their own data, and had observed the phenomenon first, they would begin to get an intuitive sense of what the shape/trend in a graph should look like. Across several labs, I asked students to generate some graphs by hand and others on Excel. In this manner, I hoped to address both the first and third research sub-questions posed above. In summary, I planned to have students graphing throughout the second and third trimesters of school.

**Timeline**

Trimester 1 – Baseline / Formative Assessments

Weeks of Oct. 9 + Oct. 16:

Estimation180 (RQ #4)

Graphing Periodic Trends and Percent Composition Labs
Week of Oct. 23

Estimation180

**Formative Assessment on Graphing: Metals and Mining** (RQ #1)

Self-confidence survey

Trimester 2 – Treatment

Weeks of Dec. 4, Dec. 11, Jan. 8

Estimation180 and Graphing Stories Warm-ups (RQ #4)

Gas Laws labs graphing (RQs #1 + #3)

Week of Jan. 15

Estimation180

Phase change graphing by hand on test (RQ #3)

Weeks of Feb. 6 + Feb. 15

Estimation180

**Atmospheric Graphing Performance Assessment** (RQs #1 + #2)

**Analyzing Scientific Data worksheet** (RQ #1)

Student interviews

Trimester 3 – Treatment / **Post-treatment Assessment**

Weeks of Mar 26 + April 2

Estimation180

Solubility Lab data and graphing (RQ #3)

Solubility curve worksheets (RQ #1)

Weeks of Apr 9 + May 7
Real-world graphs in the media analysis (RQs #1 + #2)

Week of May 7

Self-confidence survey

Student interviews

Data Collection

Data collection proceeded through five main avenues: periodic self-confidence surveys, quick checks of graphs on a scale ranging from superb to poor, detailed checks of graphs and interpretations using a more thorough rubric, student responses to Graphing Stories, and follow-up interviews to probe for more information on select topics or questions. Table 3 summarizes the research sub-questions and the data collection instruments used.

Table 3
Summary of Research Sub-questions and Data Collection Tools Used

<table>
<thead>
<tr>
<th>Using graphs to model scientific phenomena and communicate reasoning.</th>
<th>“Analyzing Scientific Data” performance assessment</th>
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<tbody>
<tr>
<td></td>
<td>Solubility curve worksheets</td>
</tr>
<tr>
<td></td>
<td>Self-confidence survey</td>
</tr>
<tr>
<td>Graphing real-world scenarios to think more about the meaning of graphs and appreciate the significance data.</td>
<td>“Mining and metal extraction” performance assessment</td>
</tr>
<tr>
<td></td>
<td>Moana Loa CO₂ graphing performance assessment</td>
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<tr>
<td></td>
<td>Graphs in the media analyses</td>
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<td>Self-confidence survey</td>
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<td>Interviews</td>
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<td>Graphing on Excel vs. graphing by hand.</td>
<td>Phase change graphs on test</td>
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<td>Solubility lab graphs</td>
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Students come in from a variety of backgrounds and are in mixed math classes, so I wanted to first ascertain their current familiarity and comfort with graphing. To do this, I had them fill out a self-confidence survey to give me more data about their comfort level with graphing. After that point, I regularly gave my students performance assessments, and tracked their progress from assessment to assessment. I also interspersed self-confidence surveys and interviews to get their perspectives on their progress. This was supplemented with graphing questions on quizzes to evaluate their ability to draw information from graphs. This combination of data collection allowed me to track which activities were most effective at improving students’ understanding of graphing and critical thinking skills, all while staying within the scope of what we ordinarily would have covered in class anyway.

I surveyed my Chemistry in the Community class throughout the course of the winter term and into the spring. At the end of the fall trimester, when they had done limited graphing in chemistry, I gave my students a self-confidence survey (Appendix A). Then, as the winter and spring terms progressed, I intersperse periods of intense graphing lessons (the AR treatment. In this manner, I was able to construct a timeline of changing student proficiency and confidence in graphing, as well as their overall analytical and critical thinking skills.
The self-confidence survey addressed the progression of skills needed to tackle a typical high school graphing performance task. The survey consists of eleven questions (plus one in-joke about our school song), beginning with more basic tasks, and then working up to more sophisticated analysis. Prior to the beginning of the AR work, students were told that this survey, along with much of the work in their class, is for a graduate school capstone project. Likewise, I told them that the survey would not be graded, and that they do not need to put their names on it. I gave students 5-8 minutes to complete the surveys, tallied the responses in Excel, and then sorted and graphed according to several criteria.

Once students had a foundation in the basic graphing skills we use in class, I began giving them a series of performance assessments (Appendices B + C). These assessments were given both during control periods and during times when using a treatment. Just as with the self-confidence surveys, students were made aware that these tasks were for research purposes for a graduate capstone. However, unlike the surveys, they were also graded for the course.

The more involved performance assessments found in Appendix C tested the students on a variety of graphing skills. They needed to analyze authentic unfamiliar data, decide upon the best kind of graph to represent the data, and then properly scale and label axes to capture the breadth of the data. Next, they were asked to analyze the data for trends and patterns, as well as to make predictions about future behavior. Finally, students needed to present their findings in some sort of persuasive narrative form. Taken together, these steps mimicked the real scientific process of making observations,
identifying patterns, and then presenting findings. The Chemistry in the Community curriculum already is set up for students to do some graphing activities, so these more-involved performance tasks fit into the syllabus naturally.

At the conclusion of my AR project in the late spring, I tasked students with finding graphs from the media to analyze. The project was open-ended, and designed to give them a chance to find an unfamiliar graph, analyze the variables studied and trends observed, and then to comment on the likely accuracy of the data and any potential biases in the author of the graph. Students completed this task twice, each time with class sharing and de-briefs of their finding. The goal here was to tie together the work done on graphing and graph analysis, and to apply those skills to interpreting and evaluating a graph that would be of interest to the general public.

This was partly inspired by a 2013 MSSE Capstone on technology and student understanding of kinematic graphs by Adam Smith, where he utilized the concept of Test of Understanding Graphs, or TUGs, that were first developed by Robert Beichner (1994). A TUG is a quick and easy graph designed to probe at a specific understanding or a specific misconception. The simplicity of the questions used to probe student understanding is evident in Figures 5 + 6 below. Likewise, these probes allowed for easy variation of the questions, and thus effective before and after assessment of student knowledge.
Figure 5: Asks students to determine the quantitative information displayed by a graph.

Figure 6: Tasks students with giving a narrative interpretation of a graph.

While in my AR project the students were finding their own “TUGs”, the method proved to be an effective instrument for measuring student progress, as I was able to collect a large amount of data \((n=9\) for both trials) and analyze it thoroughly with in-class discussion and statistical analysis. Likewise, the real-world graphs broadened the conversation about graphing from the chemistry classroom to the wider world, and allowed students to find and analyze graphs which may have been of particular interest to them.
Data Analysis Methods

There were three main methods of data analysis utilized in this study: paired t-tests, Anova analyses, and qualitative analyses. Using Excel, I conducted paired t-tests (with an alpha value set to 0.05) to look for statistically significant differences or growth in the students across various activities. Here, I assigned numerical values to student graphs, generally assigning “Superb” graphs or responses a 95%, “Good” graphs ones an 85%, “Questionable” ones a 75%, and “Poor or Wrong” ones a 65%. In this manner, I was able to quantitatively analyze and study differences between varied student works.

As discussed later in this paper, it should be noted that tasks necessarily varied in their difficulty, and thus a student submitting a “good”-rated graph on one assignment might find themselves with a “questionable” graph on a subsequent assignment, as the criteria called for analysis that is more complex. I did my best to scaffold the assignments, such that the most straight-forward analyses were presented early in the course, while more involved or abstract questions came later, and in this way, control for natural student progression. Still, the rubrics are unique to each assignment, and comparisons between assignments, and thus hard evidence of student growth, are difficult to ascertain with any certainty.

Also in Excel, I conducted Anova (two factor without replication) analyses to look for statistically significant differences in the responses to the self-confidence surveys. For this test, I clustered questions into groups, and looked for differences from October to February to May. Unlike with the performance assessments, the self-confidence surveys remained consistent across the action research period. In theory, then,
they should represent an accurate look at changing student opinion on graphing. However, by the third iteration of the survey, students were visibly bored with the task, and there is reason to believe the responses were given more out of expediency than truthfulness.

Finally, I often recorded qualitative observations about student work and critical thinking. Typically, after assigning scores to a performance assessment or other activity, I would group student work by score, and then record representative responses from each score. In this manner, I had specific examples of student work and thought processes for each level of work. This was most helpful in exploring misconceptions or areas of difficulty. Specifically, on the October performance assessment, I could establish a baseline for what the students were doing well on “superb” and “good” responses, and then identify areas of struggle from the “questionable” or “poor” responses. This was valuable to revisit in March, April, and May on the solubility lab graphing and real world graphing activities, respectively, to see if those successes and errors persisted or changed over the duration of the course.

DATA AND ANALYSIS

Introduction

The main goal of my action research was to study the effect of daily estimation activities and frequent graphing on student critical thinking. I utilized two main data sources throughout the treatment: a Likert survey and graphing performance tasks. Both the survey and the performance task were administered to a group of 10 students in my Chemistry in the Community class. The survey was initially given separately from any
instruction about graphing, and was used to probe prior understanding of graphing and comfort with those skills. It was then re-administered during the treatment and once more afterward. This survey is found in Appendix A. Detailed performance tasks on world-wide metal production and global CO₂ levels were used before and during the treatment to measure progress in graphing, and can be found in Appendix B and Appendix C, respectively.

Instruments to address the sub-question about using graphs to model scientific phenomena and communicate reasoning included a worksheet on graphical analysis with associated questions and also a worksheet on solubility curves (found in Appendices D and E, respectively). To address student performance on real-world graphing, I had them find and analyze graphs from the media twice: once for an entirely new graph to them, and once for a graph relating to a project they were working on. This assignment is described in Appendix F. To explore student critical thinking when graphing by hand versus graphing with Excel, I analyzed graphing on tests (by hand) and a solubility lab (on Excel). To address the final research sub-question about the effect of daily graphing, students sketched responses to Graphing Stories videos and then shared and critiqued those graphs with one another.

**Student Self-Confidence**

The self-confidence survey contained 11 total questions, which were divided into four distinct categories. The first probed student comfort with setting up graphs, the second their abilities to analyze data, the third their ability to interpret graphs, and the fourth asked about working with partners or presenting. Students began with the most
confidence on the statement: I can work through a difficult data set with a partner, with a 78% confidence. Students expressed the least confidence when asked about deriving an equation for a line of best fit, with a confidence of only 58%. Below, Figure 7 shows the overall confidence for the first three of those categories.

![Figure 7. Percent confidence in various graphing skills, n = 10.](image)

When asked about setting up graphs, students were least confident about the kind of graph to choose to tackle a particular problem. This would be evident in the later performance tasks and was reinforced during interviews when students responded with “difficult” and “boring” as the most common responses to a question about their feelings on graphs. Figure 8 shows the confidence of students in this cluster of tasks. Students reported a confidence of 74% for this cluster of skills, with answers to the four survey questions ranging from three “very confidents” and one “confident” by one student to three “not very confidents” and one “confident by another student.
Students in the class showed diminished self-confidence when it came to the next two clusters of skills: data analysis (Questions #5 – 7) and interpreting graphs (Questions #8 + 9). As with the interview responses above, the majority of students had negative impressions of working with graphs, writing, “I [do] not really like making graphs, my attitude [is] 50/50” and claiming that graphs are, “mindless and time-consuming.” Reflecting these attitudes, these clusters showed confidence of 68% and 69%, respectively, and are summarized in Figures 9 and 10 below.

**Figure 8.** Confidence Distribution in Setting up Graphs. Choosing the correct graph, setting bounds and scale of axes, accurately plotting points, and labelling and titling.

**Figure 9.** Confidence Distribution in Data Analysis. Drawing a line of best fit, deriving an equation, and identifying whether the trend is finite or infinite.
At the mid-point of the treatment and then a month after the treatment, I followed up by giving my students the self confidence survey again. In both subsequent sets of responses, students showed the greatest confidence in the cluster of questions about setting up graphs (79% and 83%), and the least confidence in the cluster about analyzing graphs (63% and 72%). Encouragingly, confidence in working with a partner and presenting to the class began high and remained high throughout the process.

To analyze the results, I used an ANOVA single factor test, with statistically significant results set at $p < 0.05$. The ANOVA test revealed no statistical differences in student responses to the first cluster of questions (pertaining to setting up graphs) from October to May. However, when asked about the words that now come to mind when graphing, the majority of students responded with more positive vocabulary, including “information”, “trend”, “accurate”, and “easier”.

However, the test showed statistically significant differences between the second two clusters. In terms of data analysis, student confidence grew from an average of 65% to 72%, with all responses across all three questions giving a $p$-value of 0.017. Likewise,
students reported self-confidence starting at 69% in October and rising to 79% in May for a p-value of 0.0086. As mentioned in the above paragraph, student responses to the two questions about working together did not return a statistically significant difference across the three months. When asked about their attitude toward making and interpreting graphs at the conclusion of the treatment, student language shifted to more positive responses from October, with “Definitely a lot more confident and fine with creating a graph”, “I don't hate them that much anymore, although I still don't like them”, and “Better. I enjoy making graphs a lot more than I used to.” Of the nine responses during interviews, 56% showed a positive change in their attitude, while the remaining 44% showed no change. Taken together, the ANOVA test on the student self-confidence surveys suggests a statistically significant growth in student analytical and critical thinking skills over the course of the treatment, while the interview data supports a general increase in student attitude towards the value of graphing and graphical literacy.

**Using Graphs to Model Scientific Phenomena and Communicate Reasoning**

Two separate activities were conducted to measure students’ abilities to model scientific phenomena, while an additional real-world graphing activity tested their ability to communicate their reasoning. These activities spanned the two months of the treatment period. First, students were asked to analyze and interpret sample scientific data (Appendix D). Results of that task are shown below in Figure 11.
Figure 11. Analyzing Scientific Data. Students (n=7) analyzed a pie chart, bar graph, and line graph to answer questions about average male and female height distribution.

Comparing results of the activity with student responses to the self-confidence survey given at the same time (Figure 12) reveal stark differences between their perception and the reality of their ability to accurately read and analyze graphs. As self-reported, 67% of students claim either “somewhat” or “very” confidence in analyzing data and interpreting graphs. This can be directly compared to Questions #1-4 (50% success) and Questions #7-10 (62.5%). In both cases, students reported more confidence than the results bore out.
Figure 12. Students (n=9) report a “very” or “somewhat” level of confidence of 67% for both analyzing data and interpreting graphs. This is contrasted with the actual results.

This discrepancy was reinforced when students were instead working with solubility curves over the course of a week later in the treatment period. Students were asked to study the graphs to analyze the solubility of various compounds, and then perform some simple calculations to determine solubility in amounts other than that presented on the graph. Here, 89% of students (n=9) had answers of “good” or better when reading information off the graph. However, only 56% and 33% had answers of “good” or better when doing addition or subtraction from graph data or when using ratios to scale the graph up or down. Figure 13 illustrates this decrease in performance as the tasks became more complex.
Figure 13. Downward trend in student performance becomes evident as tasks become more difficult. This trend persisted over two additional versions of the worksheet.

**Graphing Real-world Scenarios**

To address the second research sub-question about graphing real-world scenarios, I also used the formative assessment performance tasks described above (and found in Appendices B and C) in which they had to create three graphs to represent sets of data. Here, nine students completed the performance task, for a total of 27 graphs. Seven percent of those graphs could be categorized as “superb”, while the majority, 41%, are more accurately characterized as “good.” A minority, 30%, of the graphs were rated questionable. Figure 14 below summarizes the data. It should be noted that a slight majority, 52%, of the graphs fell into the lower two categories.
In addition to determining the overall quality of the graphs, it was useful to look at trends in quality between the three sets of graphs created. The first graph was supposed to be a pie chart of percentages, the second a bar graph of total values, and the third a line graph comparing two values. It would be fair to say that the first two graphs were easier to correctly select and to create than the third graph. Trends in student performance between those three graphs are summarized in Figures 15-17 below.
The results of the performance task provided an excellent baseline from which to work from. The task was designed as a formative assessment to gauge where students are in terms of their graphing ability, and several good skills as well as several gaps in knowledge were revealed. This proved helpful in guiding my instruction moving forward. Specifically, on the first problem, only two students successfully identified a pie chart as the best solution for representing the data. However, of those two, they were good at labelling and shading the wedges differently. Most students, seven of the nine, picked the wrong graphs and did not label their axes.

For the second graph, students were all correct in picking a bar graph to represent the amount of metal production in Peru. However, several opted to graph the percentage of world-wide production as opposed to the overall amount (in 1000 tons). This is not strictly incorrect, but would likely provide a less useful graph when considering the intent of the question. Getting students to recognize nuance in the specifics of a question is a task I focused on during the treatment portion of the AR. However, on this second graph,
students generally included clear labels and correct spacing increments, suggesting to me that bar graphs are quite familiar to them.

The third graph asked students to plot points on an (x,y) coordinate system and eventually to find the slope of the line that results. However, rather than x- and y-values, students were given masses of compounds. Rather than a generic slope of a line, they were trying to find a percent composition. This degree of unfamiliarity resulted in many poor graphs, and only three line graphs. Two of the three line graphs had best-fit lines that “connected the dots” rather than being a true best fit of the points. Several graphs showed breaks in the axes, which would skew a potential best-fit line. Here, lots of opportunities for growth presented themselves. Plotting data on a scatter plot and establishing lines of best fit would be revisited during the treatment portion of class in a real-world graphing activity of global CO₂ levels.

In February, while in the midst of frequent instruction on graphing and daily estimation activities to improve number sense and mathematical reasoning, students were tasked with graphing at global CO₂ levels over the last 50 years, making a prediction about levels in 2050, and defending that choice. Like the prior formative assessment task, they had to look at real-world data, pick which values were pertinent, choose a correct style graph, and then mathematically analyze the trend line for that graph to make a forward prediction. (Figure 18) shows the similar performance between these tasks.
Figure 18. On the left are the results of a real-world graphing formative assessment from October, while on the right are the results from real-world graphing in February.

While modeling in both situations produced similar results, the students’ shortcomings were exposed when asked to make mathematical estimates and communicate their findings in a written paragraph. In those two tasks, 83% of students had questionable or poor defenses of their mathematical estimates and an identical number had questionable or poor communication of their ideas. Despite the daily work in number sense and the frequent graphing, student ability to derive mathematical trends from graphs and to make predictions from those trends did not rise from prior to the treatment.

Paired t-tests were conducted to quantify changes in student performance between the October and February performance assessments. In terms of modeling scientific phenomenon (either metal mining totals or CO$_2$ emission levels), the class performance means went from 78.3% to 79.2%, which was not statistically significant ($p = 0.38$). Likewise, in terms of mathematical reasoning and quantifying, the class mean grew from 72.8% to 76.7%. However, that yielded a $p = 0.13$, which is also above the 0.05 threshold and thus does not represent a statistically significant difference. That is, both averages
trended upward, but did not show sufficient change to report the treatment as generating statistically significant growth.

Most revealing of the students’ struggles were the follow-up questions to the graphing exercise. Here, students were asked to calculate the slope of the line they plotted, describe the meaning of the slope, and then write a paragraph describing their reasoning. In this task, 86% were able to successfully calculate a slope for the entire CO\textsubscript{2} line or for segments of it, while only 29% gave a satisfactory or better answer for the meaning of the slope. This shows a competency in basic graphing skills, if a gap in the greater meaning of the graph. Likewise, in connecting the data with real-world causes, students struggled to differentiate between the questions, “What are some causes of the \textit{increase in global CO}_2\textsubscript{2} \textit{concentration} over the last fifty years?” and, “What are some causes of the increase in \textit{rate of change} of global CO\textsubscript{2} levels over the last fifty years?” (Italics mine). Whereas class discussion and the general media have given them talking points about the causes of overall increases in total CO\textsubscript{2} levels, not a single student (n = 7) was able to articulate why CO\textsubscript{2} emission rates are accelerating. Correct answers would have included increased global population and/or increased global industrialization. This exercise was illuminating, as the number sense activities and graphing exercises gave students good talking points about the meaning of the y-value and the causes of the y-value, but fell short in helping them analyze the meaning of the slope and the causes of changes in the slope of a line. This is certainly a higher order task, as it asks them to propose and defend a cause and effect scenario.
At the conclusion of the treatment period, students were asked to find and analyze graphs from the media. The full assignment is in Appendix F. While the global CO$_2$ graphing tasked them with constructing and analyzing graphs, I was also interested in their improved ability to analyze unfamiliar graphs and found graphs that were not related to the content we were studying in class. In this way, they would show their critical thinking and analysis in novel situations. The class repeated this task, the second time finding graphs that related to a modern chemistry project they were doing. Figure 19 shows the comparable results from the two trials.

![Real-World Graphing](image)

*Figure 19.* Students (n=9) were asked to find graphs from the media (Trial 1) and graphs to support their modern chemistry projects (Trial 2). Despite describing graphs related to their project, there was no significant improvement in analysis over the earlier graphs. However, performance was improved over pre-treatment results.

Beyond simply the level of correctness, student responses to the questions give further insight into their successes and challenges with critical thinking in graph
interpretation. In terms of information described, responses ranged from students describing both the x- and y-axis in a way that showed good understanding of the “x vs. y” relationship to mistaking a graph showing hemoglobin binding to be oxygen intake during exercise. Mathematically reasoning fell shortest in the question about trends. One student described the upward trend in baseball attendance, but without mention of rate, irregularities, or absolute growth. Another described a graph as “shooting up at the end”. While not one of the highest scored questions, students showed good understanding of the veracity or potential untrustworthiness of graphs, as evidenced by responses such as, “the data matches with other sources!” and “the name of the website is kind of silly, which makes me a bit concerned.” Still, some students abandoned any critical thinking with nonsensical responses such as, “I’m not super confident, but don’t feel it's all that wrong either” while another wrote “there are specific numbers and labels” as a defense of the truthfulness of the graph. ANOVA single factor testing (p < 0.05) showed no statistically significant growth in student performance from the first to the second iteration of this assignment.

Taken together, there were three major performance tasks related to real-world graphing: a pre-treatment formative assessment, the global CO₂ graphing and analysis, and analysis questions about found real-world graphs. Despite the relevance of global CO₂ levels to both their lives and the curriculum, and despite the freedom to choose two interesting graphs from the media for analysis, students did not show significant improvement in their critical thinking and interpretation during the course of the treatment. On the formative assessment, 48% of students were rated as “superb” or
“good”, while that number rose to just 50% on the CO₂ graphing. At the conclusion of the treatment (though still clearly enjoying the benefits of it), 65% of students could be considered to have “superb” or “good” interpretation of their real-world graphs. The math requirements on that assignment were less rigorous than the previous two, which may also have contributed to the improved performance.

Using Excel vs. Graphing by Hand

Williston Northampton is one-to-one with Microsoft Surface Pro 4’s, so much of the graphing that we do is digital – done through LoggerPro, Excel, or Desmos. However, on a test in January, I asked students to graph thermodynamic data by hand. This was compared directly to solubility lab data graphed on Excel the following month. In this manner, I hoped to address the differences in graphing by hand versus using Excel (Sub-question #3), and to see if student understanding of the data differed depending on which method was used.

Figure 20. Two examples of student work from a January test. Note the lack of scaling on the axes and consequent lack of correlation between physical changes and specific temperatures.
Above, Figure 20 shows two examples of graphing from a test on energy and phase changes. They are representative of the greater student work. Seventy-five percent of tests (n=10) left the axes entirely unlabeled. That same 75% showed no relation between the y-axis values and the physical changes (melting, boiling) depicted. Drawn correctly, the graphs would have flat segments during phase changes, but 25% of students drew flat segments with non-zero slopes. While likely rushing and not indicative of a greater misconception, this was a clear drawback of graphing by hand. Eighty percent of students labelled the graph with all required items, even if they did not label entirely correctly.

Upon returning the tests, we debriefed as a class about the successes and struggles with the graphing question. The next unit in the course covered solutions and solubility, and often tasked students with working with solubility curve graphs – graphs that show the maximum amount of solute that can dissolve in 100g of H₂O. Specifically, students needed to read data points off the graph and set up ratios to determine the amount of solute needed to saturate non-100g amounts of water and the amount of solvent needed to dissolve amounts of solute beyond what was depicted directly on the graph. This unit culminated in a multi-day lab where students tested the solubility of four substances in water of different temperatures, and attempted to construct their own solubility curves in Excel. Four examples are shown in Figure 21 below.
Figure 21. Student graphs depicting lab data. Note the different approaches to showing trends in solubility at different temperatures. Note as well, the third graph uses the wrong data set.

Compared with graphing by hand on the test, students produced graphs with better scaling of the axes, though this was likely due to Excel’s automated scaling. However, all student (n = 9) include a title that was at least somewhat descriptive. The graphs generated good conversation about the best way to depict trends in solubility – connecting the dots on the scatter plot of adding a line of best fit – and how the best fit line can better account for anomalous data points. Unfortunately, none of the students labelled the y-axis as being “solubility per 100g of H₂O”, and thus the magnitude of the graph was lost. A goal of the project was to investigate whether using real-world data or data generated in the lab produced better results, and comparing this activity to the
October performance assessment using a paired t-test gives p=0.115, suggesting the two results are not significantly different from one another.

**Effect of Daily Visual Exercises on Graphing**

To address the value of daily visual exercises on graphing (Sub-question #4) I utilized the website GraphingStories.com. There, users are able to submit short ~15 second videos showing some sort of motion, which students are then asked to graph. The action is first shown at full speed, then again at half-speed. The site provides a generic graph sheet that students can use as a template, though scaling and labelling the axes is left up to them. After running through three days of videos from the site (three warm-up videos per day), I also showed the class two videos I had created in the same style.

Student work was analyzed on three different criteria: accuracy, labelling, and effort/attitude. For accuracy, I was interested in their ability to interpret movement and action in mathematical terms of position versus time. Prior to the graphing, we discussed the meaning of slope, what the shape of inflection points should look like depending on the action depicted, and strategies for recording data points while watching the videos. In terms of labelling, we spent time talking about the best magnitude of the x and y-axes, as well as the importance of including units in the label. Finally, effort and attitude were more subjective, and attempted to capture student engagement with the activity over the course of the week treatment period.

As the action to be graphed grew more complex, there was a 10% decline in student accuracy. There was a dramatic 15% drop in labelling of graphs, perhaps linked to the 10% drop in perceived effort. All result summarized in Figure 22 below.
Figure 22. Student scores on accuracy, labelling, and effort of graph preparation during daily Graphing Stories exercise. The data show a statistically significant (p = .05) decline in student performance on this task.

Several of the sample graphs are shown below in Figure 23, paired with the stills from the videos the students were attempting to graph. As evidenced, there is significant variation in the accuracy and quality of the graphs made mimicking the videos, as well as the general effort put forth in the exercise.
Figure 23. Two examples of Graphing Stories videos and student graphs.

Some were labelled, while others were not. Some showed correct scaling and magnitude, others did not. Some showed specific data points that were connected, while others show more generalization about the specific movement in the videos. Not shown, as it was unfortunately not captured in data, was the rich discussion and argumentation that took place after the students shared out their graphs each day. There was excellent conversation about the shape and scale of the graphs, and the students showed both engagement in and understanding of the activity while discussing and analyzing results. This was true for a range of students, not just those who produced the more accurate graphs. It was unfortunate that in my design of the study, I failed to account for capturing these valuable moments, as they certainly provided evidence of developing critical thinking and evidence-based argumentation skills in this cohort of students.
Summary

The study can be broken down into five distinct, yet overlapping, questions: student self-confidence, graphing scientific phenomenon, graphing real-world data, graphing by hand versus graphing on Excel, and using Graphing Stories to help supplement graphing.

As self-reported, student confidence in graph creation improved by nine percent, confidence in data analysis by seven percent, and confidence in graph interpretation by ten percent. ANOVA tests showed the growth in these three areas to be statistically significant. However, changes in confidence in working with a partner and presenting were not statistically significant.

In terms of modeling scientific phenomenon, between February and April, students improved in drawing info from their graphs, making claims, and drawing conclusions. Ultimately, this allowed students to more successfully read and interpret information off graphs from the media.

Student performance in graph creation of real-world data did not improve over the course of the treatment. Students continued to struggle to generate accurate graphs and to correctly analyze trends in graphs. Paired t-tests did not show statistically significant (p = 0.38) growth in student modeling skills, despite the daily work spent on graphing. Unfortunately, it did not appear as if utilizing real-world data improved student engagement or performance over graphing sample data from the textbook.

Compared with graphing by hand on the test, students produced better graphs when using Excel. In both cases, the graphs generated good conversation about the best
way to depict trends in data and how the best fit line can better account for anomalous data points. Despite the advantages of Excel, there was still room for growth in terms of labelling, scaling, and interpreting results.

Graphing Stories generated good discussion and argumentation, despite the mixed effort that was put in up front. Students seemed interested in defending their interpretations of the action, even if there were flaws or misconceptions in those graphs. There was a statistically significant drop in quality of graphs generated as the action grew more complex and student interest waned, but the conversation during de-briefs remained valuable, showing this activity to be a low-barrier entry point to genuine mathematical conversations about graphing.

INTERPRETATION AND CONCLUSION

The primary goal of this study was to see if frequent graphing and estimation activities would improve students’ critical thinking skills. This was accomplished through four sub-questions:

1) Will requiring students to use graphs to model scientific phenomena and communicate their reasoning increase their self-efficacy?

2) Is graphing real-world scenarios or data effective at encouraging students to think more about the meaning of graphs and appreciate the significance of graphing data?

3) Do students show improved graphing ability and interest when using Excel over graphing by hand?
4) Will daily visual exercises in number sense (ie Estimation180) improve students' comfort with data and graphing and explaining their reasoning?

**Research Sub-Question #1**

To best address this sub-question, it can be broken down into distinct competency categories: drawing information from graphs, making claims, and drawing conclusions. With these three competencies in mind, several trends become apparent over the course of two observations: one before and one during the treatment.

In February, prior to the treatment, students showed only a 50% proficiency in drawing information from scientific graphs, whereas by April, that had risen to just over 93%, albeit with different graphs, which may have been easier to interpret in the second trial. Likewise, students’ proficiency with making claims rose to 89% (growth of 32%) and their ability to draw scientific conclusions rose to 84% (growth of 16%).

Conversation and feedback in class indicated to me that student understanding of the *significance* of the elements in the graph had improved over time. Whereas in February, students had trouble understanding the significance of the data points on the line graph and drawing meaningful conclusions from them, by April, they were able to talk more confidently about maximum solubility, differences in solubility between compounds, and the rationale behind why setting up ratios to scale up or scale down the graph works. The trends in these three areas are highlighted in Figure 24 below.
Figure 24. Student performance across three competency areas both before and during the treatment period. Note that the observed growth in all three areas is complicated by the task changing from month to month.

Before reading too deeply into this growth, it must again be noted that more class time was spent on the solubility graphs than on the scientific data graphs before. Likewise, the solubility graphs were integrated with the curriculum, whereas the scientific data graphing was a stand-alone activity. With these two caveats in mind, it was still heartening to see demonstrated proficiency with reading solubility graphs, and to hear accurate and mathematical discourse in class when answering questions about the graphs. In the literature, these results can be most closely compared to those of Lai, Cabrera, Vitali, Madhok, Tinker, and Lin (2016) who showed that middle-school aged students, “had difficulty linking graphs features to science concepts, especially when asked to critique or construct graphs.” That was certainly the starting point for my students, and only through extensive work with graphing did that ability improve.
Research Sub-Question #2

To measure this sub-question, I looked at growth in graphing and interpretation skills from a baseline formative assessment in October on worldwide metal mining to a second performance task in February on worldwide carbon dioxide levels. In April and May, at the end of the study period, I also asked students to collect and analyze two real-world graphs, and again looked at their interpretation skills. Figures 14-21 and 24 above summarize changes in student graphing performance and changes in analysis skill.

Paired t-tests did not show statistically significant ($p = 0.38$) growth in student modeling skills, despite the daily work spent on graphing. Likewise, there was no statistically significant improvement ($p = 0.13$) in terms of mathematical reasoning and quantifying, again despite daily estimation and number sense activities. Unfortunately, it did not appear as if utilizing real-world data improved student engagement or performance over graphing sample data from the textbook. This contrasts with the results obtained by Peterman, Cranston, Pryor, and Ruth-Allen (2015) whose work showed growth among the students when using place-based graphing. However, the results do match those of Berg and Phillips (1994) who showed a direct relationship between logical thinking and graph construction. My population of students are just beginning to develop their logical thinking skills, and thus it was expected that they would also struggle with graph creation.

The textbook data referred to global totals of metal extraction – a distant concept for my class – while the real-world carbon dioxide data is something we discussed and that appears frequently in the media. Never the less, this added immediacy or relatability
did not appear to have a statistically significant effect on student performance. As stated in the Data and Analysis section, most revealing of the students’ struggles were the follow-up questions to the graphing exercise. The hope of the study was that improved relatability of the data would increase the grit or perseverance of my students, allowing them to better analyze and interpret the graphs they created. However, only 29% could analyze the meaning of the slope to a satisfactory degree and none could satisfactorily explain why that slope was increasing. It should be pointed out that while sketching and analyzing the Graphing Stories warm-up graphs, students could often explain the “cause and effect” relationship between the movement they observed in the video and the behavior of the position vs. time graphs, yet the more abstract connection between global industrializing and accelerating CO₂ emissions escaped them.

With research sub-question #2 involving probing whether students can interpret the meaning and significance of graphs, I was also interested in students finding published graphs to analyze, and thus removing the time and potential errors involved in making and then analyzing their own graphs. Near the end of the study period, on two separate occasions, students searched for graphs in the media to analyze. As stated above, ANOVA single factor testing (threshold of p < 0.05) showed no statistically significant growth in student performance from the first to the second iteration of this assignment. However, the students’ performance on this series of tasks was much improved over the earlier trials. Student averages were in the 50% range for estimating and communicating future global CO₂ levels, and just under 30% for even interpreting the meaning of the slope on the graph. This is contrasted with an 82.5% performance on describing the
information and trends in the graphs from the media. I hesitate to state this as a strict 30-50% improvement, as the nature and level of abstraction in the tasks was different. However, it is indisputable that students did show improvement in terms of discussing the significance of trends in graphs and analyzing the factors contributing to those trends.

Research Sub-Question #3

Sub-question #3 explored whether students showed improved graphing and analysis proficiency when using Excel versus when graphing by hand. While a valid question that has been explored by other studies (see “Conceptual Framework” and the work of Jackson, Edwards, and Berger), the framework and instruments designed to explore this sub-question did not allow for as close a comparison between these two approaches as would have been ideal. Because Williston is 1-to-1 with Microsoft Surfaces, it was simply more expedient to graph on Excel, and thus the study generated just one data point for hand-drawn graphs – a January test question on heating curves. This graphing and analysis can be most closely compared to a series of lab questions in April that asked students to create and interpret graphs in Excel. Further, because it came on a test when students needed to study other topics instead of focusing their attention on the graphing task, comparing the test graphing results to the lab graphing results is speculative only.

That said, when graphing heating curves by hand, students showed exceptionally poor graph creation and interpretation skills, especially considering that the test came immediately after a week of deliberate graphing warm-up activities. Seventy-five percent (n = 10) left axes unlabeled while a different 75% did not accurately plot the data in
relation to the y-axis. It is possible that the informal nature of the warm-up carried over to the test. Whereas the warm-up provided students with a grid on which to draw, the test did not, possibly leading to the inaccurately drawn graphs. When students failed to match the phase changes to the correct temperature, they revealed a fundamental disconnect between the lab we had done on phase changes and this test question. Not accurately plotting the data shows the students knew the general shape of the graph they were expected to produce, but did not fully grasp the significance of the y-values they were plotting, and placed them somewhat arbitrarily. That is, they knew the shape was significant, but not that the specific values (ie melting and boiling points) on the shape were as well. This speaks to the results of Jackson, Edwards, and Berg’s work, where they found that the drudgery of plotting by hand left less time for students to think about the design or interpretation of the graphs. A goal of this study was to help students recognize graphs as valuable tools to depict data and events, and unfortunately, this test question revealed that students had recollections of the general shape of the graph, but lacked the understanding that the very specific temperatures on the graph depict physical properties of a substance, and are not arbitrary or variable.

Research Sub-Question #4

The final research sub-question probed the connection between the daily warm-up exercises Estimation180 and Graphing Stories and students’ abilities to accurately and correctly graph and explain their reasoning. As presented in the “Data and Analysis” section, student performance showed a statistically significant decline over the three days of the Graphing Stories warm-up activities. The stories to be graphed did increase slightly
in complexity over the three days, offering one explanation for the drop. From student attitude and reactions during class, however, this drop-off may have had more to do with boredom or perceived monotony at the task. That, in of itself, is a valuable insight, as the students on the whole revealed minimal interest in improving their graphing or in discussing the successes and struggles of the peers in the daily de-briefs.

To help tease apart the cause of the decline in student performance, it is valuable to pair the Graphing Stories performance with the results of the February self-confidence survey given at the same time. While there was not a statistically significant difference between the October and February self-confidence surveys, there was a trend upward (from 74% to 79%) in students’ self-reported ability to accurately create graphs. This growth, however, must be balanced with a corresponding decrease (from 69% to 65%) in students’ confidence with “correctly identifying the relationship shown” in an unfamiliar graph, such as the Graphing Stories videos.

Estimation180 was used as a warm-up activity for the duration of the study. Each class period, students were asked to make an estimate and defend it with mathematical reasoning. Requiring a mathematical defense should have gotten students used to thinking about and describing the world in mathematical terms, and thus increased their fluency with using graphs to quantify and model real-world phenomenon. However, as stated above, there was not a statistical significant improvement in the scores on performance tasks from the beginning to the end of the study. Like with the Graphing Stories exercise across three days, the lack of improvement across three months can
perhaps be attributed to student apathy rather than a failure of the treatment. This will be discussed further in the “Values and Claims” section.

The treatment culminated with two rounds of an activity where students needed to find and analyze real world graphs of their choosing. The hope was that the extensive work with Graphing Stories and looking at the behavior of non-chemistry graphs would prepare students to analyze additional real-world graphs. However, like Whitacre and Saul (2016) found, “Although these students could successfully complete school assignments related to graphs, their skills in reading authentic, real-world science communication was limited.” Certainly, context provides aids in discussing and interpreting graphs, and the struggle the students faced with these culminating exercises showed just how important that context can be. In the words of the earlier study, it proved difficult to relate graphical representations with natural language.

Summary

The study began with 10 students in the course, and ended with only nine. This was clearly a small sample size, yet still large enough to yield meaningful results and data interpretation. The triangulation matrix generated multiple quantitative data points per student across a range of skills. Interviews, class discussion, and evaluation of student work provided supplementary qualitative data to further elucidate the research.

Despite a lack of demonstrable growth, the results of the real-world graph interpretation from April and May provide a succinct measure of some success in this study. The overarching research question to be addressed was: will daily graphing and estimation exercises improve student efficacy with graph creation and interpretation.
Looking at the mixed, but promising, results from collecting, analyzing, and discussing found real-world graphs suggests that most students ended the course with an ability to do so. That is, while the results of the individual sub-questions may have yielded mixed results and no statistically significant growth, the ultimate goal of preparing students to think critically about graphical information they encounter in their everyday life was evidenced by the end of the research period.

**VALUE**

**Introduction**

Graphing is an essential scientific skill in the classroom and as a scientifically literate member of the population. “Good graphs,” writes Howard Wainer, “make complex problems clear” (A Trout in the Milk, 2005). Thirteen years after he wrote those words, the young adults in high schools across the country who will soon become voters face a political landscape ever more filled with statistics, trends, percentages, and complex interactions. Good graphs, and the understanding of those good graphs, can help those future voters to become critical thinkers and skeptical analyzers of misleading narratives. In my Chemistry in the Community course, and specifically in this study, I sought to bestow in my students the ability to analyze and critique graphical information, and then to make informed decisions about that information. Specifically, through the research question and sub questions, I sought to gauge student self-confidence, graphical literacy, and overall scientific literacy across a variety of tasks and activities.
Self-Confidence

Over the course of the treatment, the data show a clear upward trend in student self-confidence. There were increases in self-confidence in the ability to construct and analyze a graph of their own creation, and in the ability to analyze a graph given to them. Despite these increases, the data do not show an increase in student performance of either of these tasks. One of the goals of the study was for students to take more ownership of their learning, and increased self-confidence would be the first step in the process. Unfortunately, the students seemed to be responding to the survey questions based on how they thought they should be improving, not on how they were actually improving.

An interesting next step would be to explore techniques to improve this meta-cognition. Additionally, I can show future classes work from this year that demonstrates either proficiency or specific errors and areas for improvement for each assignment. More deliberate self-analysis of their work after a given task, and comparing their work against exemplar work, should help students more accurately gauge their self-confidence.

Likewise, giving the students a concrete check-list for constructing graphs will help ensure they meet minimum baselines, and then can focus more time on analysis and interpretation. A goal of this study was to explore students’ abilities to calculate slopes and then interpret the meaning of that slope. Attempting to do so using graphs without proper spacing or axis labels showing scale makes the first task impossible and the second meaningless. That is, a simple checklist of the “features of a quality graph” should improve student confidence in simply constructing graphs and allow more time for in-depth analysis.
Graphical and Scientific Literacy

In this study, graphical literacy was defined as, “The ability to create an accurate graph from data, to analyze a graph through discussion of trends, slope, and/or extrapolation.” The study did not support a statistically significant increase in students’ abilities to create, mathematically analyze, or interpret the trends in graphs. However, the interview results and class discussions both suggest an overall improvement in student appreciation for graphs and enjoyment of working with graphs. Further, this treatment exposed students to graphs as efficient and effective conveyers of information about topics as wide ranging as nineteenth century British birth rates, worldwide iron ore extraction, MLB stadium attendance trends, and the effects of water temperature on solubility. I’d like to continue to explore ways to incorporate real-world data into the course. Students expressed the highest levels of self-confidence with regards to working together and presenting, so I would like to give them more opportunities to do so with regards to their findings and interpretations on that real-world data.

During the Graphing Stories activities, student discourse during the peer critiques was both enthusiastic and mathematical. Here, when the graphing activity was low-stakes (ungraded), seemingly non-chemistry related, and technology-focused, the students showed more buy-in and enthusiasm than was typical for the more traditional chemistry assignments. Just as their motivation and accuracy suffered in the more difficult performance tasks, the students struggled in Graphing Stories as the action to be graphed became more complex.
Since Graphing Stories proved to be so engaging for the students, I would like to begin future sections of this course with this accessible introduction to graphing. Fostering an early understanding and appreciation for graphs as well as having early mathematical conversations about the meaning of slope and other graphing components would then transfer to our chemistry-focused graphing work later in the course. In this manner, I would hope that students in subsequent classes would exhibit better work on the more complex performance tasks that this year’s students struggled with.

Beyond graphical literacy, a goal of Chemistry in the Community and of this study is to increase the scientific literacy of the students. Reading and analyzing a graph is the first step, though appreciating the underlying cause and effect behind that scientific graph is even more important. ChemCom strives to expose students to the general principles of an introductory high school chemistry course such as materials and their properties, gases and the atmosphere, matter and energy, water and solutions, and so on. Each unit begins with a case study introducing the main ideas via a real-world problem, and is replete with data and graphs to connect the material to that case study and other real-world applications.

For instance, Unit 4: Water begins with a river fish kill in a fictional town, and later introduces students to solubility trends for solids and gases, asking them to speculate on how temperature and solubility may contribute insight into possible culprits for a dissolved agent in the water that was responsible for the fish kill. Using this section as a springboard, the class then looked at lead ion levels in Flint, MI and seasonal variation in dissolved oxygen levels in local water sources – both sets of data presented in graphical
form. This study continually asked students to look at cause and effect, and in this activity, they were asked to comment on the causes, effects, and possible solutions for very real issues. By understanding the graph – the variation, magnitude, and possible extrapolation of the data – and being versed in a basic scientific background, the students were prepared to present their observations and discuss potential solutions to a non-expert audience, thus replicating the very real process that scientists go through when their work intersects with public policy.

To help reinforce this progression, I need to continually ask questions to probe students’ reasonings and how they arrive at their conclusions. Estimation180 provides the first steps in this direction, as I constantly ask students to defend their reasoning mathematically, rather than with vague or specious reasoning such as “I feel like CO$_2$ levels would double…” A great place to practice this mathematical reasoning in a graphical setting is with the real-world graph analyses, which could be done earlier and repeatedly throughout the year. This past year, one student chose a graph on toxicity, and proceeded to make some unsubstantiated claims about relative levels of toxicity. Here, either during one on one conference or in a larger peer review setting, would be an ideal time to encourage looking at the numbers and data available to defend that claim. An alarming claim made during peer review this year was, “his reasoning looks correct because he used numbers to defend it.” This student quote from April shows that much more still needs to be done with this group to help them gain the graphical and scientific literacy skills to the point where they can differentiate between the presence of numbers and the correct interpretation of those numbers.
Conclusion

I recognize that not all students (or even, any students) in this class may go on to become USGS or EPA-affiliated scientists. Yet the work of those scientists, and others, will very much be in the news and public eye, and understanding the data and rationale will remain an important skill. Results of the graph creation and interpretation exercises yielded mixed results and no statistically significant growth, and at times, student apathy about the graphing assignments was apparent. Yet the conversation in describing the real-world graphs that students were tasked with finding was intelligent and genuine, perceived self-confidence levels rose, and interview results showed that the views on graphing of a majority of students improved. These students will continue to see graphs in their future science courses and in the real world, and my confident hope is that they will appreciate them just a bit more than before.

For my part, I would like to think about ways to continue this AR in future years on a smaller and more focused scale. The overall research question – will daily graphing and estimation improve graphing and critical thinking? – still seems plausible, even if the data from this study do not convey a definite result. It is my hope, as well, that frequent real-world activities and genuine classroom discourse and argumentation will instill in my students fond memories of chemistry class, and give them reason to continue studying science and chemistry as they continue their education.


APPENDICES
APPENDIX A

STUDENT SELF-CONFIDENCE SURVEY
<table>
<thead>
<tr>
<th>Graphing Steps</th>
<th>How Confident Do You Feel? (Circle One)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I can identify the kind of graph required based on the data</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>2. I can correctly set the bounds and scale of the axes</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>3. I can accurately plot points or create bars/columns</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>4. I can properly and informatively label axes and title the graph</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>5. I can draw a line of best fit to match the data, if appropriate</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>6. I can derive an equation from a line of best fit</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>7. I can identify whether the trend is finite or will continue</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>8. For an unfamiliar graph, I can determine the variables being compared</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>9. For an unfamiliar graph, I can correctly identify the relationship shown</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>10. I can work through a difficult data set with a partner or group</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>11. I can describe the steps to turn data into a graph in front to the entire class</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
<tr>
<td>12. I know all the words to Sammy</td>
<td>Very  Somewhat  Not Very  Not at All</td>
</tr>
</tbody>
</table>
APPENDIX B

GLOBAL IRON ORE GRAPHING PERFORMANCE ASSESSMENT
Graphing Prompts

1. Consider the data from Table 1.4 (pg. 85). What kind of graph is most appropriate for representing the countries most responsible for the worldwide production of aluminum? Prepare and label such a graph.

2. Consider the data about Peru from Table 1.4. What kind of graph is most appropriate for representing the annual production of metals mined by Peru? Prepare and label such a graph.

3. The table below shows the results from a variety of experiments run to determine the percent of carbon and oxygen in various samples of carbon monoxide (CO). Note: although there are one atom each of carbon and oxygen, because those atoms have different masses, the percent composition of CO is not 50% carbon and 50% oxygen. What kind of graph could represent this data and be used to determine the correct percent composition of one of the elements? Prepare and label such a graph.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Total Mass (g)</th>
<th>Carbon (g)</th>
<th>Oxygen (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
<td>3.2</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>13.1</td>
<td>5.6</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>2.09</td>
<td>0.89</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>232.2</td>
<td>99.2</td>
<td>133</td>
</tr>
<tr>
<td>5</td>
<td>37.4</td>
<td>16</td>
<td>21.4</td>
</tr>
<tr>
<td>6</td>
<td>53.67</td>
<td>22.90</td>
<td>30.77</td>
</tr>
</tbody>
</table>
APPENDIX C

GLOBAL CARBON DIOXIDE GRAPHING PERFORMANCE ASSESSMENT
Performance Assessment #1 – Atmospheric CO₂ Data

You are a scientist who works at Mauna Loa observatory in Hawaii who measures CO₂ concentration in the atmosphere. You have data from the last 50 years ([http://www.esrl.noaa.gov/gmd/ccgg/trends](http://www.esrl.noaa.gov/gmd/ccgg/trends)). You are presenting to the governor about your data, including a prediction about what the CO₂ level will be in Hawaii in the year 2050. In order to create your prediction you will need to determine if it should be modeled by a linear or exponential function based on the rate of growth.

<table>
<thead>
<tr>
<th>Modeling</th>
<th>Content</th>
<th>Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Makes assumptions and approximations to simplify a real-world situation</td>
<td>Provides in context an estimate for 2050 based on the model chosen and assesses reasonableness in comparison to other models beyond linear and exponential</td>
</tr>
<tr>
<td>3</td>
<td>Correctly maps relationships between important quantities</td>
<td>Provides, in context, an estimate for 2050 based on the model chosen and assesses reasonableness.</td>
</tr>
<tr>
<td>2</td>
<td>Selects appropriate tools to create models</td>
<td>Provides an estimate for 2050 based on the model chosen.</td>
</tr>
<tr>
<td>1</td>
<td>Analyzes relationships mathematically to draw conclusions</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses all data from website</td>
<td></td>
<td></td>
<td>Uses data from website without distinction</td>
<td>Uses partial data from website</td>
</tr>
<tr>
<td>Compares equation output to given data</td>
<td></td>
<td></td>
<td>Graphs an equation which model CO₂ levels vs time</td>
<td>Identifies time vs. CO₂ levels</td>
</tr>
<tr>
<td>Uses data from website and spreadsheet</td>
<td></td>
<td></td>
<td>Uses a graphing calculator</td>
<td>Uses graph provided on website</td>
</tr>
<tr>
<td>Draws conclusion based on models and interprets results</td>
<td></td>
<td></td>
<td>Draws limited conclusions based on model and interprets some results</td>
<td>Draws a conclusion but fails to show evidence of interpreting results</td>
</tr>
</tbody>
</table>

Total = / 12

Task and rubric adapted from: Colorado Department of Education, Power to the Variable Performance Assessment [http://www.cde.state.co.us](http://www.cde.state.co.us)
APPENDIX D

GRAPHING SCIENTIFIC DATA WORKSHEET
Analyzing and Interpreting Scientific Data

Why?

When scientific investigations, scientists gather data and present it in the form of charts, tables, or graphs. The data must be properly collected, analyzed, and interpreted to allow scientists to make informed decisions regarding the validity and usefulness of their observations. The charts, graphs, and tables are used to present scientific data in a clear and concise manner, which allows others to understand and interpret the results.

Model 1 – Graphs and Charts of Classroom Measurement Data

Pie Chart

- Percentage of Males and Females by Height

Bar Graph

- Comparing Male and Female Average Heights

Line Graph

- Distribution of Height in Males and Females
1. According to the data in Model 1, how many females fall within the range 146-153 cm tall?

2. According to the data in Model 1, how many males are 185 cm or above in height?

3. Using the graph(s) in Model 1, determine the approximate average height of males and of females.

4. Refer to the data in Model 1.
   a. How many males are taller than 179 cm and approximately what percentage of the total is that?
   b. Which graph(s) illustrate the answer to the previous question?

5. Which type of graph or chart in Model 1 shows a side by side comparison of data?

6. Which type of graph or chart in Model 1 shows trends in data over time?

7. Describe two trends in male and female height using the line graph.

8. Use complete sentences to compare the presentation of height data in the three graphs. Discuss any information that is based on one or more graphs, and any unique information that is available on each.

9. If you were to test if a correlation exists between the height of an individual and his/her hand length, what would be the best type of graph/chart to make? Explain your reasoning.

10. What conclusions can you draw comparing the height, hand length, and knee/eight of males and females? State your conclusions in complete sentences.
APPENDIX E

SOLUBILITY CURVE WORKSHEETS
You add 45g KNO₃ to 100g H₂O at 60°C. To what temperature must the solution cool before solid begins to precipitate out?

You saturate 100g H₂O with NaNO₃ at 60°C. The solution cools to 20°C. If you agitate the solution, how much NaNO₃ will precipitate out?

How much H₂O at 50°C is needed to fully dissolve 17.3g Ce₂(SO₄)₃?

How much KClO₃ is needed to saturate 85g H₂O at 36°C?

You attempt to dissolve 65g of NH₄Cl in 100 mL of H₂O at 40°C. How much will dissolve? How much more H₂O must be added to fully dissolve all the solid?
You add 35g KNO₃ to 100g H₂O at 50°C. To what temperature must the solution cool before solid begins to precipitate out?

You saturate 100g H₂O with NaNO₃ at 70°C. The solution cools to 30°C. If you agitate the solution, how much NaNO₃ will precipitate out?

How much H₂O at 50°C is needed to fully dissolve 27.3g Ca₂(SO₄)₂?

How much KClO₃ is needed to saturate 185g H₂O at 36°C?

You attempt to dissolve 55g of NH₄Cl in 100 mL of H₂O at 35°C. How much will dissolve? How much more H₂O must be added to fully dissolve all the solid?
APPENDIX F

GRAPHS IN THE MEDIA ASSIGNMENT
Find a graph in the media. Ideas for where to look are in the class notebook: Unit 4 >> Labs >> Graphs in the Media. Typing a topic of interest into Google and selecting "Images" is a good idea, too.

Copy your graph into OneNote and answer the following questions about it. Export this page as a .pdf, and submit it to the Dropbox.

1. Describe where you found your graph. What website or source was it on? Was there an article with the graph? Provide a link to the graph.

2. In your own words, in a sentence, what information is being described by the graph?

3. In a complete sentence, what trend do you observe in the data? Be specific.

4. In a complete sentence, how confident are you in accuracy of the graph in depicting the information? In a second sentence, give a specific reason for your level of confidence.

5. Is your information strictly factual? Is there the possibility for some bias in the information? In a sentence or two, comment on the likelihood that the graph-maker was trying to make a point with the graph. Here, you may want to return to the source of the graph.

6. In a sentence or two, describe whether this information would be best displayed visually (as a graph), in table form (raw data), or in narrative form (sentence summaries). Comment on any advantages or disadvantages to displaying the data one way or the other.