JOURNAL OF CHEMICAL EDUCATION

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Article

The Scientific Method as a Scaffold to Enhance Communication Skills in Chemistry

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Cite This: *J. Chem. Educ.* 2022, 99, 2338−2350

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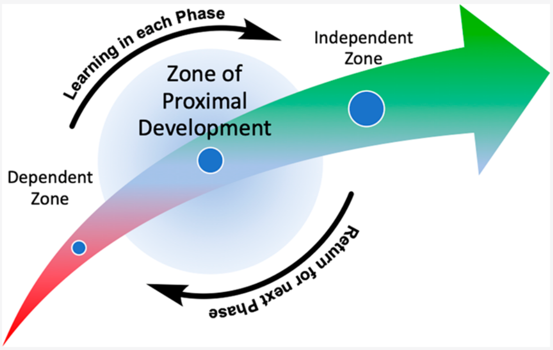
ABSTRACT: Scientific success in the field of chemistry depends upon the mastery of a wide range of soft skills, most notably scientific writing and speaking. However, training for scientific communication is typically limited at the undergraduate level, where students struggle to express themselves in a clear and logical manner. The underlying issue is deeper than basic technical skills; rather, it is a problem of students' unawareness of a fundamental and strategic framework for writing and speaking with a purpose. The methodology has been implemented for individual mentorship and in our regional summer research program to deliver a blueprint of thought and reasoning that endows students with the confidence and skills to become more effective communicators. Our didactic process intertwines undergraduate research with the scientific method and is partitioned into six steps, referred to as "phases", to allow for focused and deep thinking on the essential components of the scientific method. The phases are designed to challenge the student in their zone of proximal development so they learn to extract and ultimately comprehend the elements of the scientific method through focused written and oral assignments. Students then compile their newly acquired knowledge to create a compelling and logical story, using their persuasive written and oral presentations to complete a research proposal, final report, and formal 20 min presentation. We find that such an approach delivers the necessary guidance to promote the logical framework that improves writing and speaking skills. Over the past decade, we have witnessed both qualitative and quantitative gains in the students' confidence in their abilities and skills (developed by this process), preparing them for future careers as young scientists.



KEYWORDS: *Communication/Writing, Undergraduate Research, Curriculum, First-Year Undergraduate/General Audience, Second-Year Undergraduate, Upper-Division Undergraduate*

INTRODUCTION

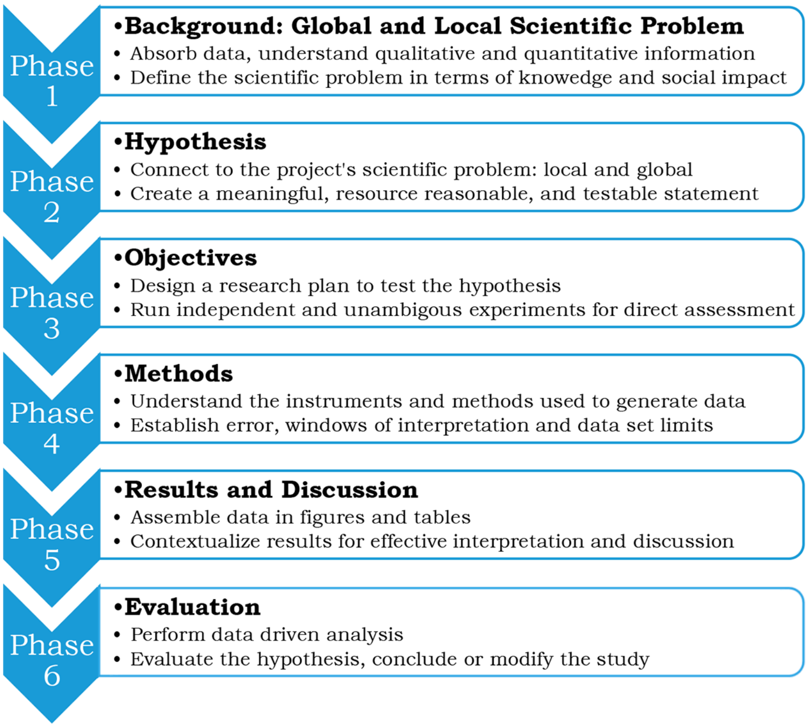
Effective communication skills are no longer considered a luxury in chemical enterprise. Instead, meaningful writing and persuasive speaking for a broad range of audiences have become integral parts of the standard core professional skills required for scientific and professional success in the workforce[1−7] and graduate school.[8−17] Despite recent discourse emphasizing the importance of scientific communication, especially in a scholarly sense, it is a perennial problem originating at the undergraduate level.[18,19] It is well documented that undergraduate science students frequently struggle with written[20−26] and oral[27−33] communication skills.[3,34−42] This persists into graduate school,[8−17,43−47] the medical fields,[48−50] and the workforce.[4,28,30,31,51] To meet this challenge, educators have been urged to adopt curricular changes that will foster strong communication skills in their students.[3,24,25,51−65]

The literature surrounding chemical communication pedagogy is diverse. However, efforts to improve written and oral communication skills have followed four general and broad approaches, which are sometimes presented in a hybrid form: (1) the incorporation of technical writing with chemical literacy,[66−77] in first-year courses,[39,66,67,78−83] stand-alone classes,[27,43,69,79,84−96] and/or discipline specific courses;[70,97−115] (2) laboratory experiments;[21,26,32,59,69,107,116−127] (3) critical thinking exercises;[3,13,26,117,128−143] and (4) research experiences.[134,144−155] Despite the community's best efforts, a host of factors, which were identified early on, continue to present significant barriers for engaging and enhancing the communication skills of

Received: February 10, 2022
Revised: April 11, 2022
Published: May 9, 2022

https://doi.org/10.1021/acs.jchemed.2c00113

Scheme 1. Individual Phases and Underlying Goals Associated with the Designed Program Framed by the Scientific Method



•Background: Global and Local Scientific Problem

- Absorb data, understand qualitative and quantitative information
- Define the scientific problem in terms of knowedge and social impact

•Hypothesis

- Connect to the project's scientific problem: local and global
- Create a meaningful, resource reasonable, and testable statement

•Objectives

- Design a research plan to test the hypothesis
- Run independent and unambigous experiments for direct assessment

•Methods

- Understand the instruments and methods used to generate data
- Establish error, windows of interpretation and data set limits

•Results and Discussion

- Assemble data in figures and tables
- Contextualize results for effective interpretation and discussion

•Evaluation

- Perform data driven analysis
- Evaluate the hypothesis, conclude or modify the study

undergraduate students. These include the quickly changing modes of information access, availability of instructional material, priorities of faculty, and limited librarian access.[156−159]

Moreover, the issue with communication skills has been postulated to be a consequence of how chemistry is typically taught, with emphasis placed on building a student's knowledge base as opposed to teaching them how to communicate that knowledge effectively.[25,26,160] Specifically, critical thinking is a particularly difficult skill to teach.[128−130,133] Consequently, addressing these concerns is a priority in many science departments across the country, with work being done to improve students' communication skills and to align the institution's instructional methods with national guidelines,[31] including those of the American Chemical Society.[161] This has inspired a diverse set of strategies with a variety of outcomes over the past decade. A number of groups have used scientific writing as a tool to improve student critical thinking skills.[13,24−26,131−133,140]

The application and explicit steps of the scientific method,[19,144,162−171] either to understand real world scenarios easily[144] or to digest more esoteric scientific topics,[134,145] have been reported as an excellent method for teaching the skill of problem solving.[172] Over the past 18 years, we have expanded on this work and developed a unique protocol to enhance the communication skills of undergraduates. During this time, we have experimented, refined, and reflected on practices that have and have not been effective. Our successful didactic process encourages critical and deep thinking within the isolated steps of the scientific method. Segmenting the scientific method into well-defined, stand-alone segments allows students to focus and achieve mastery of each step of the scientific method, with the expected outcome of developing clear, sharp, and thorough answers to framing questions concerning their specific research. At the end, students splice the knowledge generated from each phase into a single cohesive and meaningful scientific story, which is communicated both orally and in writing. In this report, we specify how we have leveraged the scientific method along with the community's reports on technical writing for chemical literacy,[27,39,43,66−115,119] laboratory experiments,[21,26,32,59,107,116−127,173−175] critical thinking exercises,[3,13,26,117,128−143] and research experiences[146−155] to create a unique protocol to enhance the communication skills of undergraduates via individual one-on-one mentoring. This has been applied to our regional summer research program of roughly 35 students per year.

■ METHODS

Discussion of our novel approach using the scientific method as a blueprint to enhance both writing and speaking skills is segmented into six sections, where the critical barriers and efforts supporting the curriculum are addressed. The sections involve discussion of theories implemented (Section 1), different phases of the scientific method used to scaffold learning (Section 2), program implementation for enhanced communication (Section 3), and program outcomes involving delivery of a proposal (master plan), final report, and symposium presentation (Section 4).

1. Pedagogical Theory

To develop students' written and oral communication skills, we target their zone of proximal development (ZPD)[176−178] (see the graphical abstract) in each of the individual, manageable steps of the scientific method, referred to as "phases". The ZPD is an idea put forward by Vygotsky, which proposes that students[179,180] learn best when challenged to learn/apply new information and skills that are close to and build on what they already know, often under the guidance and mentoring of someone with more knowledge and experience.[181,182] While Vygotsky originally studied child development, this theory has been established as being an effective tool for all learners, including undergraduates[183,184] and graduate students.[185] Targeting the ZPD of each learner in each phase of the scientific method is central in our methodology, since students have a diverse range of skills and confidence when starting a research project. Identification of each student's ZPD allows us to focus on an individual's weakness or starting point for instruction. For each student in each phase, their ZPD is easily located by assigning basic tasks inherent to each phase of our methodology, as will be described in detail for each phase. Once in the student's ZPD, the idea is to support them by giving general encouragement, direct demonstration, and feedback for specific written and oral assignments. This builds their skills so that they can traverse to independence and mastery of each phase of the scientific method.

2. Alignment of Phases with the Scientific Method

One of our first observations when developing our program of study was that many undergraduates had only a superficial understanding of the scientific method. Some could recite the different stages of the method, but it became clear to us quickly that undergraduates entering research for the first time, independent of their academic year, had neither a deep nor a critical understanding required for meaningful research. In all aspects of the scientific method, the students lacked a systematic, controlled, and critical approach. Consequently, the students could not articulate the entire process into a compelling, coherent, and complete scientific proposal. The main issue is that the students did not have a conceptual picture, or blueprint, to guide them strategically and logically in constructing a sound scientific plan of action. Our efforts in teaching the individual components of the scientific method stress that a quality scientific study must be a complete and connected story, presented clearly and in concise terms. Moreover, all portions of the scientific method are equally important, such that the weakest link defines the overall quality of the investigation.

The steps (phases) of our program (Scheme 1) are aligned with the scientific method to create a scaffold for the students, having them focus on well-defined issues to remove distractions and encourage deep thinking on specific aspects of their work.[186] Our program starts with the most basic form of cognition: remembering, understanding, and assembling factual information from their project's background to define the scientific problem (Phase 1). The second phase requires the student to piece together their understanding from Phase 1 and apply it by articulating a hypothesis (Phase 2) and developing associated experiments (Phase 3) to create a research plan. The experiments and data generated require an appreciation of the instruments, protocols, and the methods used to establish boundaries for error analysis for interpretation (Phase 4), discussion, and analysis of the resulting data (Phase 5). Finally, the students evaluate the data against their hypothesis to decide if the study is finished or needs to be extended (Phase 6).[187]

Two phases implicit in the scientific method (Phases 1 and 4) were added, based on our experience, to address commonly observed deficiencies explicitly and scaffold their ability to communicate. Phase 1 was added so that students would expand their knowledge, take ownership of the project, develop a sense of curiosity, and be able to defend the motivation for their research. Phase 4 was added because we realized that students did not invest appropriate effort into understanding the instrumentation, methods, or protocols used to generate data. This phase mandates that students consider the measured natural phenomena at particular length and time scales, and most importantly the intrinsic/extrinsic error associated with their data, so that they can later draw meaningful conclusions.

Overall, our six-phase method is designed to increase the rigor and depth of scientific inquiry appropriate for undergraduate instruction. The mentor can help the learner by creating appropriately challenging activities, or scaffolding the learning, and can even push the learning further through the ZPD by modifying how and what they are scaffolding.[178,186] Ultimately, we have found that requiring explicit and specific answers to key tasks provided in each "Box" (see Boxes 1−6 below) tied to each phase of the scientific method (Scheme 1) is the most effective methodology. Explicit examples, activities, and exercises are described in detail in the respective phases below.

Phase 1a: Global Scientific Problem. We quickly discovered that simply giving students a research problem could unintentionally limit their scientific growth. When starting, most students are either eager to make progress on their project and perceive the generation of data as the immediate first step, or they simply do not appreciate the value of understanding the background that contextualizes the scientific problem of interest. Either way, students display a tendency to skip over the foundational knowledge that lays the groundwork for their original idea. It is important that the student discover, with guidance or through imitation, what problem the research mentor has identified. As discussed in the pedagogy section, the intent is to expand the knowledge of students, and encourage their ownership, sense of curiosity, and ability to defend the rationale supporting their work. As such, we implemented Phase 1 to ensure that the students understand the necessary background information to articulate the scientific problem in terms of the contribution to knowledge and societal impact of the project.

However, to broaden students' knowledge, we have found it necessary to scaffold the scientific problem into "global" and "local" terms to help them differentiate between the goals of the scientific community (global, Phase 1a) and that of their specific research objective (local, Phase 1b). This explicit separation brings clarity to the students and assists in both written and oral forms of communication. We stress to the students that the significance or impact of science performed is only as good as the scientific problem identified.

The first step for the students is to comprehend the global scientific problem. The students initially discuss the nature of the problem with their research mentor(s) and then carry out a literature search to develop an understanding of the background and establish the status of the scientific field. We have found a wide range in students' abilities to search the literature effectively, depending on if they have been previously exposed to this skill or not and to what extent. We provide instruction through a 30 min lecture transforming into a 30 min workshop that concludes with assignments on the basics of how to use different search engines effectively[92] and provide details on search strategies applied to their specific research agenda.[93,188,189] Along with their mentor(s) guidance, the student then frames the global problem in a way that makes sense to them, which is typically an iterative process. Moreover, by framing the global scientific problem at the beginning, it allows the student to establish a firm footing and sharpens their perspective on their individual contributions. This allows them to communicate effectively what their project is, and, more importantly, why they are doing it with other scientists and the public. Additionally, this phase involves the student reading primary and secondary scientific literature, frequently for the first time, which not only has the benefit of improving their background knowledge, but also exposes them to how published scientists communicate, and initiates the scientific habit of scouring the literature.

Phase 1b: Local Scientific Problem. Paired with the prior “global scientific problem”, the “local scientific problem” defines the students’ specific efforts and immediate scientific problem in relation to the global scientific problem. Understanding the connection between an overarching research program and their individual project is important in promoting project ownership, ability to communicate, and an increase in their breadth and depth of knowledge. Clarity between global and local issues helps students appreciate the logical, financial, and resource factors that dictate why scientific problems are broken into smaller tasks and systematically solved.

Phases 1a and 1b serve as the topic for the first round of written and oral communication assignments in our program. After the first stage of literature searching, it is necessary to target a student’s ZPD in terms of both the global and local scientific problem. To accomplish this, the students work closely with their research mentor(s), and frequently with more experienced group members, such as graduate students and older undergraduate researchers, to provide direction and feedback in establishing a foundation of background knowledge.

To identify the student’s ZPD, facilitate deeper understanding, and foster critical thinking, the students are tasked to address the tasks in Box 1 with single sentence concise answers. We adopt a “student-initiated approach”, where students draft the first version of an answer, then refine that answer with the mentor(s) providing feedback to guide the student toward mastery of each stage. It is stressed with the students that formulating answers to these questions is an iterative process, requiring considerable effort to express answers in a meaningful and concise manner. We have qualitatively observed that student answers change as they gain more confidence in their abilities and their knowledge expands throughout the research experience. The responses they craft then act as focal points in both the written and oral forms of communication that are the ultimate goal of Phase 1.

Box 1. Phase 1 Tasks

1. State the global scientific problem.
2. Define your local scientific problem, and how it connects to the global problem.
3. List the major contributions in the field, then logically assemble those contributions to define the scientific problem in both local and global terms.
4. Give any general background that is necessary to understand your local and global problem.
5. Clearly explain how your contribution will impact science and society.

Phase 2: Hypothesis. A significant observation, and one that inspired our efforts in developing this course of action, involved the students’ inability to formulate a hypothesis and make a connection to the scientific problem. The development of a strong hypothesis is a notable challenge for many students initially as they have not previously needed to develop one independently, let alone understand the factors that strengthen a hypothesis.[190−192] However, once the students have working global and local versions of their scientific problem, they develop a hypothesis for their research (Phase 2) under the guidance of the mentor(s). We stress to the students that the success, quality, and significance of science performed is only as good as the hypotheses. To scaffold students as they create a hypothesis, we emphasize four important characteristics (rubric): (1) Know clearly what you want to learn; (2) Ensure that it connects to the well-defined scientific problem; (3) Confirm that it is testable, falsifiable, and delivers a clear outcome; and (4) Verify that it is reasonable in terms of time, effort, and resources. It is important that the mentor(s) guide the students to a strong hypothesis through an iterative process, using our student-initiated approach. Mentors provide feedback to the students with the rubric given above as they progress. As students repeatedly edit their hypothesis, they move through their ZPD for creating a strong hypothesis, thereby gaining mastery over the skill.

Phase 2 serves as the topic for the second round of written and oral communication assignments in our program. As in Phase 1, a series of tasks, given in Box 2, provide the targets for a deep and clear understanding of hypothesis development. Consistent throughout our program, we push students to provide concise, single-sentence answers to facilitate clarity, understanding, and ownership. In fact, restriction in writing is a known challenge, which has been shown to inspire creativity and clarity.[193,194] Specifically, we had some success in using the original limits of Twitter: 140 characters, but witnessed a few problems, where many but not all clear and concise answers fit within the constraint. Currently, we do not explicitly give a character maximum, but we find that 200 characters as an upper bound (approximately 40 words, in one to two sentences) works well as a constraint. This is also an excellent time to work with the students on learning that a hypothesis is neither right nor wrong and disproving their hypothesis does not equate to failure. As with the prior phase, the responses to these tasks will become central points for the student’s written report and oral presentation.

Box 2. Phase 2 Tasks

1. State your hypothesis.
2. List the major contributions and logically assemble those ideas to define your hypothesis.
3. Enumerate alternative ideas or pathways.
4. Connect your hypothesis back to the scientific problem of interest.

Phase 3: Experimental Design. Once a meaningful scientific problem has been identified, and an impactful hypothesis developed, a research agenda needs to be formulated. This step is another significant challenge for students, as most receive virtually no training in designing experiments to address a hypothesis.[195] Farley has recently pointed out that the generally accepted approach of introductory laboratory courses involve detailed step-by-step protocols, often referred to as “cookbook-style” laboratories, to teach and reinforce basic laboratory skills. Although necessary, such a curriculum falls short in providing students with opportunities to design and plan experimental protocols and troubleshoot problems in scientific experimentation.[196−198]

Therefore, it is of little surprise that undergraduates taking on research experiences struggle and that our program of study needs to provide opportunities to foster student development of experimental design skills.[199]

Students that have mastered Phase 2 typically encounter the least amount of frustration in developing experiments to test their hypothesis. To scaffold students as they create their experimental design, we emphasize four key factors: (1) the experimental design should directly address the hypothesis; (2) plan independent, alternative avenues, in case the first plan fails; (3) the experiments should deliver clear and unambiguous data; and (4) be reasonable in terms of time, effort, and resources. It is important that the mentor guide the student to a strong experimental design through an iterative process, using our student-initiated approach. As they repeatedly edit their experimental design, they move through their ZPD, thereby gaining mastery over the skill.

Phase 3 serves as the topic for the third round of written and oral communication assignments in our program. Initial questions deal with the number of experiments, or objectives, needed in the research agenda. We typically make reference to the "Rule of Three"[200] writing principle that suggests that a trio of events is more effectively communicated and satisfying than other numbers. However, we stress that the number of experiments is really determined by the number needed to evaluate the hypothesis completely. A series of tasks, given in Box 3, provide the targets for experiments and associated objectives to interrogate the hypothesis, which is an essential step in the scientific method.

Box 3. Phase 3 Tasks

1. Provide an overall schematic that outlines the logical flow of your experimental design.
2. Give each research objective and/or specific aim with anticipated outcome.
3. Summarize and/or review the critical articles that support each objective.
4. List potential pitfalls for each objective/specific aim.
5. State how the outcome for each objective/specific aim connects back to your hypothesis.

Ultimately, we encourage students to anticipate the data necessary to definitively evaluate the hypothesis and to plan the experiments accordingly. The experiments that generate this data are the basis for each research objective.

Phase 4a: Instrumentation and Methods. The scientific method assumes that instruments and the data generated are fact based and completely understood. However, we have found that undergraduates do not necessarily have experience in using advanced instrumentation due to limited access or lack of training required for modern equipment. Additionally, many of the students have an incomplete understanding of the underlying physical phenomena behind spectroscopy and spectrometry. Consequently, we quickly learned that we needed to supplement our method to reinforce the skills and knowledge of students and we added this phase.

Phase 4 serves as the topic for the fourth round of written and oral communication assignments in our program. We start Phase 4 by forging a connection between the experimental design of Phase 3 and the required instruments for data generation. Specifically, during this phase, we task the students with (1) identifying the instruments, methods, and protocols used in their experimental design; (2) learning the underlying physical principles used to measure natural phenomena; (3) locating and reviewing recent literature that uses said techniques; and (4) acquiring training for proper, safe, and responsible usage. We promote reflective thinking by the students about why they are implementing techniques and what they are measuring. Many times, students will simply do the experiments they are told to do with the apparatus they are told to use without questioning why. By making the students justify why, they are forced to consider things more deeply and demonstrate higher order cognitive skills on Bloom's taxonomy, such as analysis and evaluation.[187] This ensures that they have not only mastered the basic levels of knowledge but also understand what they are doing deeply and complexly. With a mastery of the techniques and extended knowledge base, students have a heightened sense of confidence when communicating with their peers through an open forum and with outside faculty through written documents.

Box 4. Phase 4 Tasks

1. State why each instrument, method, or protocol in each step of the experimental design is used.
2. Identify the natural phenomena being measured for each instrument or technique.
3. Critique the sources of error and give a possible error analysis.
4. List and review articles that use the instruments and techniques of interest and ascertain how error is treated.

Phase 4b: Sources of Error. Another significant observation is that when students use an instrument to generate data, they frequently ignore the error associated with the measurement. Appreciation of error is critical since it is a centerpiece of data interpretation and discussion. To underscore the need to respect error in the measurement process, the students are required to think critically about their experiments and determine the intrinsic sources of error within their experiments, along with other potential sources of error. This may include things such as limits of detection for various analytical instruments, environmental contaminants, variability in instruments like a mass balance, and inherent limitations of computational methods. Phase 4 reinforces the importance for the students to be constantly aware of error, that way they can draw meaningful conclusions from their data and identify the limitations in the methods they are using.

Phase 5: Results and Discussion. We find that students are mostly prepared for Phase 5 from the training received in traditional laboratory classes. The tricky part was to reach this phase with meaningful data that flows in a logical and consistent scientific story. In the discussion of the results, it is important to display the data using appropriate tables, figures, and schemes. Students start by deciding which data to present and the form of presentation. Again, students are guided by their mentors using our established methods. The second and less challenging part is to make the figures, tables, and schemes presentable for effective communication. We advocate that formats should be consistent and aligned with guidelines, as given by the American Chemical Society.[64]

Similar to the previous phases, students will need to not only present their data, but also contextualize it with respect to their

Box 5. Phase 5 Tasks

1. List and justify how each figure, table, or scheme contributes to the logical evaluation of the experimental design.
2. State the main interpretation derived from each figure, table, or scheme, respecting the error analysis.

experimental design and hypothesis for effective interpretation and discussion. This is a nontrivial skill and will be something that they will need in their future careers. It necessitates conveying complex concepts as clearly and concisely as possible. The fact that our process is iterative helps to scaffold student learning, as they have presented their background before and can use prior weeks' experiences to improve this and future presentations.

Phase 6: Evaluation. At the end of the research project, the students will need to continue to reflect on what they have accomplished and forge a connection between all the phases in developing a complete and concise scientific story. As the final part of our method, it is important for them to examine critically if they have supported or disproved their hypothesis, with justification, demonstrating the higher-level cognitive skills they have acquired.[187,201,202] Moreover, they will work with their research mentor(s) to ascertain what the future of the project will look like and how the foundations they established will build toward readdressing the local and global problem (Phase 1a and 1b). This will likewise involve higher-level cognitive skills as the students analyze and evaluate the work they have done to draw their conclusions and create a plan to move forward.[187,201,202]

Box 6. Phase 6 Tasks

1. Give your results, interpretation, error analysis, and conclusion for each objective.
2. Discuss how the data relates to each objective and either supports or refutes your hypothesis.
3. Is the study finished? If so, then clearly define the intellectual merit and broader impacts.
4. If not, then how and why has the hypothesis changed? Where does your plan go next? Relate how your work and future work connects back to the scientific problem of interest.

3. Enhanced Communication

To implement the program, we divided the entire cohort into two groups, which presented on alternating weeks. Each group was typically composed of approximately 14−18 students, with returning and/or more experienced students presenting during the first week and newer students going second, in order to learn by observing their more experienced peers. The participating faculty of 7−10 members during the summer was led by a faculty mentor designated as the "faculty coordinator". Every week the students from one group submitted a written document on that week's phase to the participating faculty and gave a 3 min oral presentation, with the other group submitting their documents and presenting the following week. As described below, most of the learning occurred the week before the documents were submitted and presented, when each student worked with their mentor(s) to prepare the oral and written presentations.

The topic for both the presentation and written document are linked to each phase of our program (Scheme 1), starting from the scientific problem defining their research and moving through the designated phases toward a cumulative presentation at the end of the summer. As the students move through the phases toward their final presentation, they constantly revisit and refine the core concepts of prior weeks with guidance, improving their communication skills and depth of understanding. This repetition with appropriate scaffolding moved the students through their zone of proximal development to challenge them in new ways, with the goal of expanding the two core zones. This subsequently led to increased student confidence, as they improved their ability to work independently, working through the zone of proximal development, as visualized in the Figure 1.

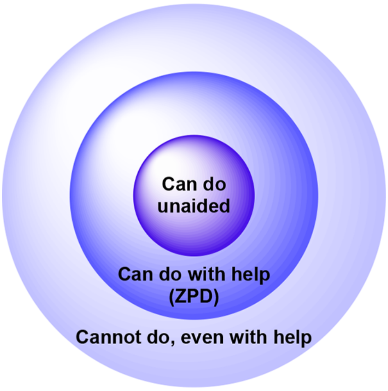


Figure 1. Different zones of learning end with skills that the learner has mastered and can accomplish unaided in the center, and start with what the learner cannot accomplish, no matter how many tools or how much aid is given in the outer zone. Nestled between the two is the Zone of Proximal Development, or the what the learner can accomplish with assistance. This is the ideal zone to target when teaching.[176−178]

Written Component. As students progress through the phases, they regularly prepare and submit one-page written reports describing a specific aspect of their research project. They work with their research mentor(s) the week before the due date to craft the document using the student-initiated approach, receiving frequent feedback on tone, pacing, focus, and scientific principles. As each phase of the scientific method builds on prior information, the papers increase in complexity throughout the program, with the student incorporating earlier feedback to improve their writing iteratively. This moves them through their zone of proximal development and challenges their higher order thinking skills so that they can achieve mastery of the process. Following submission, a faculty coordinator assigns two nonmentor faculty members to read, critique, and provide feedback to the student. This step was established to mimic the peer review process, provide the student with feedback from experts in their field, and highlight how effectively the student is communicating their ideas to educated nonexperts (faculty who work in different fields). These faculty peer reviewers are rotated throughout the summer so that each student receives feedback from the majority of participating faculty, ensuring a broad audience. Once the student receives the feedback, they work with their faculty mentor(s) to revise their written document and apply the lessons learned to future assignments. Frequently this involves the students reaching out to the reviewers and working with them to clarify and refine their communication skills.

Oral Component. Paired with the written documents, the students prepare 3 min oral presentations. These presentations are given to the entire summer cohort during the REU, an intimidating task for many students. Prior to their presentation, the students write their document as described in Section 2, identifying many of the key concepts for that phase (see Boxes 1−6). They work with their research mentor(s) to assemble an oral presentation covering that week's topic. The length of 3 min for the oral presentation was selected to emphasize brevity as well as clarity, consistent with the ideas underscoring constraint in writing.[27,193,194] The short time has numerous advantages; it requires the student presenters to address the topic for that week directly (such as their hypothesis for Phase 2), and do so in a way that is understandable to an audience with a wide range of education levels and prior knowledge.[27] Following the presentation, the student receives feedback from faculty members in the audience, aimed at showing the students where they need greater clarity and how to present their information better. Akin to the written document, the students use this experience to improve their presentations iteratively for the following phases. Moreover, the students become more comfortable with presenting to and answering questions from a large group over the length of the summer program. This entire process is repeated five times (not including the final presentation), allowing the students to improve through iterative, scaffolded cycles of writing and presentation, feedback, critique, and refinement.

4. Program Outcomes

Master Plan and Final Report. The "master plan" is the proposal stage of the research experience. Construction of the master plan is introduced during a workshop early in the first week of the program with the goal of defining a rough but meaningful starting point for the student to build and refine upon. The master plan serves as the student-initiated starting proposal, directed and enhanced by Phases 1−4 in our methodology. There is no page limit, and the format is guided by the National Science Foundation format for single investigator proposals. Consequently, for the master plan, students (1) learn how to identify, critique, and approach problems important in science and society; (2) learn to build a strong hypothesis; and (3) assemble an experimental design for their project. In essence, the master plan is the first stage in the research experience that promotes students to make meaningful and compelling scientific arguments that deliver a deeper appreciation for the scientific method through reflective and critical thinking. The master plan is a living document that is routinely updated and expanded by the student throughout their research experience.

Once data is acquired, analyzed, and evaluated, in Phases 5 and 6 the document transforms from a proposal format. Starting at Phase 5, the master plan evolves into a manuscript or final report. The students receive instruction on how to construct, collect, interpret, and draw conclusions in our program. The format taught is consistent with the guidelines provided by the American Chemical Society (ACS).[63,64] Overall, students (1) gain a deeper appreciation for the scientific method through reflective and critical thinking; (2) develop valuable scientific writing and presentation skills through frequent practice with feedback; (3) explore the difference between a proposal and a manuscript; and (4) reveal opportunities that stimulate their scientific interest and their career pathway.

Symposia. The combined experience from the oral presentations in each phase builds up to a final presentation of the entire research experience. Within our curriculum, students are first taught to take deep and critical considerations of issues and concepts in the scientific method. For the final presentation, the student is taught to use the information garnered and adjust syntax based on the target audience, anticipate questions, and present a complete and compelling story. As part of our scaffolding, we encouraged the students to "speak simply" as advocated by the ACS.[203,204] Students give presentations in either poster or oral formats at two or more of the following: the final Duquesne Regional Symposium (typically attended by more than 120 students); the annual URAN|UM (Undergraduate Research University of Michigan) Conference at Ann Arbor MI (virtually); the ACS National Meeting and Exposition; other national symposia, such as Experimental Biology; and back home at their own undergraduate institutions.

■ RESULTS AND DISCUSSION

Over the 18 years that we have run this program, we have had over 560 students successfully matriculate and move on to become independent scientists. These students have gone to graduate school, other professional programs, or entered the workforce directly. Moreover, faculty involved in the program have noted that the student presentations and written documents have had a positive impact on student communication skills. Along with this, the novel use of the scientific method as a framing tool has helped keep students on track and moving through the program. This has been paired with more quantitative data (SI), which has been used to track student confidence with scientific skills.

■ CONCLUSIONS

Our strategy of incorporating iterative writing and speaking exercises with individual mentoring during our summer research programs has helped students develop confidence in scientific communication and gain a deeper familiarity with the scientific method. We scaffolded their learning by dividing the scientific method into six distinct phases: (1) Background, (2) Hypothesis, (3) Objectives, (4) Methods, (5) Results, and (6) Evaluation. By having the students move through the phases of the scientific method, we scaffold how to become more effective communicators. Moreover, we used the iterative nature of the exercises to build students' higher-order cognitive skills, preparing them to formulate their own questions, and providing the tools to answer them rationally. This helps them progress through their zone of proximal development, expanding their central area of comfort, and preparing them to act as independent communicators in the future. Our survey data (SI) support the conclusion that our program of study increased student confidence in their ability to leverage the scientific method in guiding their ability to communicate in a written and oral format. Likewise, we have qualitatively observed an improvement in students' critical, concise, and logical communication skills since the introduction of this teaching method. This curriculum is well suited for use in other departments and will be beneficial for all participating students, regardless of what field of science they gravitate toward. By leveraging the scientific method as a conceptual framework, we have created a curriculum that can be implemented easily in any program, helping students improve their communication skills.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00113.

Survey Data and Analysis (PDF) (DOCX)

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The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

Support from the National Science Foundation is acknowledged for the Research Experiences for Undergraduates (REU) (CHE-1950585), Major Research Instrumentation (MRI) (CHE-1726824), and Scholarships for Science, Technology, Engineering and Mathematics (S-STEM) (DUE-1259941). Support from Duquesne University's School of Natural and Environmental Sciences is also acknowledged. In addition, the faculty in the Department of Chemistry and Biochemistry at Duquesne University is gratefully acknowledged for their support and implementation of this program.

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