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We Have More in Common than We Think: A Comparison of Scientific Skills and Disciplinary Practices in the Guiding Documents for Biology, Chemistry, and Mathematics

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ABSTRACT

Students are encouraged to develop a set of scientific skills and disciplinary practices common across the STEM disciplines. These skills (scientific inquiry, quantitative skills, laboratory and computational skills, communication skills, teamwork/interpersonal skills, interdisciplinary competency) are highlighted as important in discipline-based guiding documents—biology (Vision and Change in Undergraduate Biology Education: A Call to Action), chemistry (American Chemical Society Guidelines and Evaluation Procedures for Bachelor's Degree Programs), and mathematics (A Common Vision for Undergraduate Mathematical Sciences Programs in 2025)—for undergraduate teaching of biology, chemistry, and mathematics, and for the professional success of STEM college graduates. To promote interdisciplinary teaching and learning of STEM, we present a comprehensive comparison of the different disciplines' competency statements for undergraduate education. This organization and comparison of commonalities in scientific skills and disciplinary practices can be used by faculty and departments to come together to break down traditional silos, help their students more easily apply learning from one STEM discipline to another, and to create institutional change.

KEYWORDS
Guiding documents; Biology; Chemistry; Mathematics; Scientific skills; Interdisciplinary STEM; introductory STEM courses

1. Introduction

In science, technology, engineering, and math (STEM), solutions to research problems require the bridging of several disciplines such as chemistry, biology, mathematics, and computer science. Pressing challenges such as climate change and the COVID-19 pandemic have emphasized the importance of interdisciplinary collaborations in the STEM workforce. (Kurup et al., 2021) To become successful professionals, students are encouraged to develop a set of skills including scientific literacy, communication, and data management that are common across STEM disciplines. (Blanchard et al., 2021; Carnevale et al., 2011; Co, 2019) Although some of these skills are traditionally considered "soft skills" (such as communication), they are increasingly considered key parts of a scientist's work. However, STEM instructors often undervalue the teaching of these skills in their classroom, in part because of: (1) the difficulty in assessing mastery of these skills, (2) the lack of formal training in teaching science communication, (Brownell et al., 2013) and (3) the need to cover the required content in a course in the time allotted. (Dewsbury et al., 2022; Petersen et al., 2020) However, these soft skills are highlighted as important in discipline-based guiding documents—biology (Vision and Change in Undergraduate Biology Education: A Call to Action (Bauerle et al., 2011)), chemistry (American Chemical Society (ACS) Guidelines and Evaluation Procedures for Bachelor's Degree Programs (American Chemical Society Committee on Professional Training, 2015)), and mathematics (A Common Vision for

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Undergraduate Mathematical Sciences Programs in 2025 (Saxe & Braddy, 2015))—for undergraduate teaching of biology, chemistry, and mathematics, and in other documents targeting the professional success of STEM college graduates. (e.g., National Association of Colleges & Employers, 2021).

The guiding documents for all three disciplines were written for different audiences and different purposes. The chemistry document is geared towards institutions that have been approved to award ACS certified bachelor's degrees, and provides guidance for associate's degrees in chemistry. Biology's Vision and Change and Mathematics' Common Vision guiding documents arose from diverse collaborative efforts among stakeholders, and they present more far-reaching recommendations for the future of biology and mathematics. However, each discipline discusses similar ideas with language that is specific to the discipline, and herein, we have aligned these ideas into more general themes.

Despite the push for interdisciplinary teaching and efforts to bridge disciplines, the norm for STEM education is to have individual departments delineate curricula and design assessments that evaluate STEM disciplines independently, presumably using each discipline's guiding document(s) (Gao et al., 2020). A comprehensive comparison of the competency statements for undergraduate education of biology (Bauerle et al., 2011), chemistry (American Chemical Society Committee on Professional Training, 2015), and mathematics (Saxe & Braddy, 2015) would be valuable in developing an integrated STEM curriculum. Such comparison is the core of this manuscript, and led us to identify common skills and practices. We chose to focus on biology, chemistry, and mathematics since these disciplines are addressed in the first year of a biology major, often one of the largest STEM majors at colleges and universities. We engaged in a line-by-line, close reading of the guiding documents, and categorized the skills and practices identified therein. Representatives from all three disciplines, as well as from both two-year and four-year institutions, were involved in these discussions. We define scientific skills (SS) as the overarching abilities that are important to the study and practice of science, e.g., communication skills in the scientific context. We define disciplinary practices (DP) as what each discipline does to promote these skills, e.g., being able to write a laboratory report. They expand upon the eight career competencies that employers seek from all college graduates (career and self-development, communication, critical thinking, equity and inclusion, leadership, professionalism, teamwork, and technology), as enumerated by the National Association of Colleges and Employers (2021), as well as those collected by the American Council on Education. (Taylor & Haras, 2020)

Explicit alignment of common SS & DP in biology, chemistry, and mathematics would both help students to understand the application of what they are learning in one class to another class, and to apply learning from one STEM discipline to another STEM discipline. Ultimately, helping students understand that these skills are transferable across disciplines will increase their success in their foundational mathematics and science courses—sometimes defined as a STEM meta-major (Baker, 2018; Schudde et al., 2020; Waugh, 2016)—and enable students to engage in multi-disciplinary projects in upper-level courses and as professionals (Kelley & Knowles, 2016).

In addition to the alignment of common SS & DP, we briefly suggest some ideas that STEM instructors could implement in their classroom to facilitate the teaching of commonalities between disciplines. We hope that this is an impetus for educators in other STEM areas, e.g., physics and engineering, to complete similar analyses.

2. Results and Discussion

The alignment compares the general scientific skills and the specific disciplinary practices (SS & DP) presented in the guiding documents from the three chosen STEM disciplines: biology, chemistry, and mathematics. Herein, we discuss the broad SS categories that developed as a result of this work. In the process of identifying common SS categories, DPs were placed where they are most applicable, rather than in multiple categories. For example, we placed 'managing and analyzing data sets' from the biology guiding document only in our Quantitative Skills category, although in the biology guiding document, it is duplicated in their Lab/Computational Skills category.

In reviewing the guiding documents for biology (Bauerle et al., 2011), chemistry (American Chemical Society Committee on Professional Training, 2015), and mathematics (Saxe & Braddy, 2015), we found that while the categories and languages were different, commonalities emerged, resulting in a set of six general scientific skills categories: *Scientific Inquiry* (Table 1), *Quantitative Skills* (Table 2), *Laboratory and Computational Skills* (Table 3), *Oral and Written Communication* (Table 4), *Interdisciplinary Nature of Science* (Table 5), and *Teamwork and Interpersonal Skills* (Table 6). Under each category are more specific scientific skills which

Table 1. Scientific inquiry and the associated disciplinary practices.

Scientific Skills	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Understanding process of science	**B1.** Understand process of science	**C1.** Use chemistry in the scientific process	
Developing/testing hypotheses	**B2.** Experimental design **B3.** Hypothesis testing **B4.** Evaluation of experimental evidence	**C2.** Design and execute experiments **C3.** Develop testable hypotheses **C4.** Draw appropriate conclusions from data **C5.** Understand uncertainty in measurements	**M1.** Design and execute experiments **M2.** Develop testable hypotheses **M3.** Draw appropriate conclusions from data **M4.** Understand uncertainty in measurements
Developing problem solving Skills	**B5.** Developing problem solving skills	**C6.** Apply all subdisciplines of chemistry to solve problems	**M5.** Be able to reason and problem solve

Table 2. Quantitative skills and the associated disciplinary practices.

Scientific Skills	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Quantitative reasoning	**B1.** Develop and interpret graphs	**C1.** Develop strengths in quantitative problem-solving and application of mathematical skills	**M1.** Analyze and produce mathematical data in multiple forms (e.g., equations, graphs, diagrams, tables, words) and be able to convert from one form to another **M2.** Develop quantitative skills
Applying statistical methods to analyze data	**B2.** Applying statistical methods to diverse data **B3.** Manage and analyze large data sets **B4.** Applying informatics skills	**C2.** Analyze data with appropriate statistical methods	**M3.** Analyze data with statistics **M4.** Be prepared for careers in statistics and data science

Table 3. Laboratory/computational skills and the associated disciplinary practices.

Scientific Skills	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Hands-on laboratory experience	**B1.** Participate in authentic research experience	**C1.** Obtain hands-on basic laboratory skills **C2.** Laboratory experiences that involve experimental design, execution, data analysis and use of chemical literature. **C3.** Synthesize and characterize organic and inorganic compounds	
Using modeling and simulation to investigate questions, phenomena, and problems	**B2.** Ability to use modeling and simulation **B3.** Computational modeling of dynamic systems **B4.** Incorporating stochasticity into biological models	**C4.** Ability to use computational chemistry software **C5.** Ability to compute chemical properties and phenomena to complement experimental work	**M1.** Ability to use technology effectively to solve problems **M2.** Ability to use technology as an aid in exploring mathematical ideas **M3.** Use of technology should occur with increasing sophistication throughout a major curriculum

Table 4. Communication skills and the associated disciplinary practices.

Scientific Skills	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Oral and written communication	**B1.** Scientific writing **B2.** Communication with other disciplines **B3.** Explain scientific concepts to different audiences	**C1.** Write well-organized and concise reports in a scientifically appropriate style **C2.** Present information in a clear and organized manner **C3.** Use relevant technology for communication	**M1.** Ability to communicate mathematical/quantitative ideas clearly and coherently both verbally and in writing to audiences **M2.** Communicate with different types of audiences

students are expected to master upon completing a STEM degree that the guiding documents of biology, chemistry, and mathematics essentially agree upon. Under each specific scientific skill (SS) are the STEM disciplinary practices (DPs) for each discipline. These DPs often differ among fields while supporting learning of the same SS. The absence of a disciplinary practice indicates a lack of emphasis in the guiding document. In the Tables, phrases are either adapted or taken directly from the disciplinary guiding

Table 5. STEM interdisciplinary competence and the associated disciplinary practices.

Scientific Skill	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Use knowledge from all areas of math and science in interdisciplinary problem solving	**B1.** Tap into interdisciplinary nature of science **B2.** Apply concepts from other sciences to interpret biological phenomena **B3.** Collaborating across disciplines	**C1.** Solve problems by combining knowledge from multiple fields of chemistry **C2.** Provide experiences beyond chemistry content knowledge **C3.** Develop competence in other critical skills outside of chemistry	**M1.** Become aware of connections to other areas. **M2.** Learn to apply mathematical ideas in other areas **M3.** It is critical that the math community plays a role through research and education in areas such as bioinformatics, finance, engineering, data analytics, and computer science

Table 6. Teamwork/interpersonal skills and the associated disciplinary practices.

Scientific Skills	DPs: Biology	DPs: Chemistry	DPs: Mathematics
Work in teams	**B1.** Work with teammates to establish and periodically update group plan and expectations	**C1.** Work with others to productively solve scientific problems, both as leaders and team members	**M1.** Learn to collaborate through team projects and internships
Work with people with diverse backgrounds, skill sets, and perspectives	**B2.** Cross-cultural awareness	**C2.** Work efficiently with a diverse group of peers	

documents. (American Chemical Society Committee on Professional Training, 2015; Bauerle et al., 2011; Saxe & Braddy, 2015)

The scientific skill category of *Scientific Inquiry* is broken down into three SS: (1) understanding the process of science, (2) developing/testing hypotheses, and (3) developing problem solving skills (Table 1). Then, under each discipline, the associated DPs are listed. The biology and chemistry guiding documents both require an understanding of the process of science, with the chemistry document being more specific by stressing the understanding of the role of chemistry in the scientific process (see B1 and C1 in Table 1). Conversely, the guiding document for mathematics does not emphasize the understanding of the process of science as a DP. However, the guiding documents of all three fields require the ability to develop and test hypotheses by designing meaningful experiments (see B2, B3, C2, C3, M1, and M2), and all emphasize the ability to appropriately evaluate the results from experiments (see B4, C4, and M3). The mathematics and chemistry guiding documents additionally state that students should be able to understand uncertainty in measurements, a skill that is important in both designing experiments and interpreting their outcomes (C5 and M4), whereas biology does not explicitly focus on experimental uncertainty. As expected, all disciplines emphasize the ability for students to be able to solve problems (see B5, C6, and M5), with chemistry emphasizing that a student should possess the ability to use different subdisciplines of chemistry to do so (C6).

The scientific skill category (SS) of *Quantitative Skills* is broken down into two SS areas: quantitative reasoning and applying statistical methods to analyze data (Table 2). DPs for quantitative reasoning for biology students focus on being able to interpret graphs (B1 in Table 2). The guiding document of mathematics takes this idea further and suggests that students should be able to analyze and produce mathematical data in forms such as graphs, tables, equations, diagrams, and words, as well as being proficient in converting one representation of data into another (M1). The DP for chemistry is somewhat different in that, rather than proficiency with graphs and other mathematical visualizations, it focuses more on general math/quantitative proficiency, a DP that is shared with mathematics (C1 and M2). All three guiding documents contain DPs about using statistics to analyze data (B2, C2, and M3). Biology has additional DPs in *Quantitative Skills* on managing large sets of data as well as applying informatics skills that the other disciplines do not share (B3 and B4). While this is a difference, there is fundamental agreement among all three disciplines on the importance of learning statistical analysis. This commonality may be a way to develop a multidisciplinary statistics course taken by biology, chemistry, and mathematics majors. Further emphasizing the importance of statistical analysis, mathematics has a DP of being prepared for a career in statistics and data science (M4).

While there is much agreement among the three disciplines in the scientific skill category of *Quantitative Skills*, the same is not true for the scientific skill category of *Laboratory/Computational Skills*, especially regarding laboratory skills (Table 3). The DPs for biology regarding hands-on laboratory experiences are broadly mentioned as participation in authentic research experiences, whether that is in the field, in the research laboratory of a professor, through a Course-Based Undergraduate Research Experience (CURE), (Auchincloss et al., 2014; Dolan, n.d.; Martin et al., 2021) or through researching the literature *via* a Consider, Read, Elucidate hypothesis, Analyze and interpret data, Think of the next Experiment (CREATE) process (B1 in Table 3). (Hoskins et al., 2007, 2011) The DPs for mathematics do not suggest laboratory skills, which reflects the relative importance of a laboratory component in the practice of chemistry or biology vs. mathematics (Table 3). Chemistry is a field that revolves around the laboratory and this is reflected in its DPs. Chemistry students should possess many skills ranging from safe laboratory practices to preparing solutions and use of various laboratory equipment (C1, C2, and C3). Chemistry DPs also specify that the DPs of the SS category *Scientific Inquiry* should be applied in a laboratory setting, namely developing testable hypotheses, designing and executing experiments, and drawing appropriate conclusions from data (Table 1).

Despite the differences in the DPs regarding laboratory skills, the three disciplines all agree on the importance of using computational programs to enhance the understanding of math and science and to prepare students for their careers (Table 3). All three disciplines focus on using computers to model and explore phenomena (see Table 3: B2 - B4, C4, M1, and M2). Additionally, chemistry has a DP that specifies that computational work should complement experimental work (C5), while mathematics has a DP specifying that the technology used should increase in sophistication as a student progresses through the major (M3).

The SS category of *Communication Skills* is also of central importance in the guiding documents of biology, chemistry, and mathematics (Table 4). As seen in entries B1, C1, C2, and M1, DPs in the three fields highlight the importance of excellence in communication, whether it is in scientific writing or verbal communication. In contrast to the larger differences in the DPs of *Laboratory/Computational Skills* (Table 3), there are minor differences in the DPs for *Communication Skills* (Table 4). The guiding document for chemistry specifies that students should become proficient with a variety of technologies for communication, while there are no specific corresponding DPs in biology or mathematics (C3). The guiding documents of biology and mathematics call for the ability to communicate with different types/levels of audiences, while chemistry does not have a specific DP for this (B3, M2). Biology goes as far as having a DP for communicating with other disciplines (B2), which is related to the next SS category of *STEM Interdisciplinary Competence* (Table 5).

Biology, chemistry, and mathematics have DPs that fit under *STEM Interdisciplinary Competence*, but this SS category is approached quite differently depending on the field. Biology emphasizes collaborating across disciplines and focusing on the interdisciplinary nature of science (B1 – B3). The Biology DPs describe "interdisciplinarity" as how other disciplines can be used to understand biology (B2). For example, students should be able to use physics to understand dynamic systems in biology and use chemistry to understand the molecular interactions in biological systems. Mathematics, on the other hand, has DPs that focus on how math is connected to and can be applied to other disciplines and the fundamental importance of math in fields such as bioinformatics, finance, engineering, data analytics, and computer science (M1 – M3). The chemistry guiding document differs from the other two disciplines as it focuses on using different subdisciplines of chemistry to solve problems, with less emphasis on fields outside of chemistry (C1). The DPs in chemistry in this SS that reference other fields state that chemistry majors should gain experience and develop competence outside of chemistry (C2 and C3).

Working with other disciplines also requires teamwork and interpersonal skills, and each guiding document speaks to these skills, thus we have defined a separate scientific skill category of *Teamwork/Interpersonal Skills* (Table 6). Regarding teamwork, while the DPs may be phrased differently, all disciplines emphasize the ability to work effectively in a team (B1, C1, M1). Biology and chemistry have additional DPs that students should be able to work with others that have diverse cultural backgrounds from themselves (B2, C2). Mathematics does not specifically have this DP, although the importance of a diverse student population is emphasized in all three guiding documents.

For the complete alignment table of the scientific skills and disciplinary practices, containing extended passages from the original guiding documents, see Supplementary Materials.

With these alignments now in place, we suggest some possible actions (Table 7) that could be taken to integrate these commonalities into the classroom.

Table 7. Suggestions for using the alignment.

Scientific Skill	Suggested Implementation
Developing and Testing Hypotheses	Consistently use Claim, Evidence, Reasoning as the standard for written reports in laboratory courses. (Model Teaching, 2019)
Quantitative Reasoning	Create shared common exercises that teach and assess students' understanding of shared quantitative skills among disciplines such as interpreting and making graphs or dimensional analysis.
Applying statistical methods to analyze data	Use example data from multiple disciplines when teaching statistics.
Using modeling and simulation to investigate questions, phenomena, and problems	Create a common presentation to highlight how software is used in each discipline.
Oral and written communication	Have a common rubric among disciplines for oral presentations and for laboratory reports and/or notebooks pegged to student year.
Oral and written communication	Have students present their research to introductory courses from different disciplines.
Use knowledge from all areas of math and science in interdisciplinary problem solving	Using data or explaining phenomena from another field to illustrate what is being learned in a field. Example: integrations being used in kinetics. Another example: identify polar and nonpolar amino acids in a biology class.
Work in teams	Create and use a common reflection document across STEM disciplines to assess teamwork.
Work with people with diverse backgrounds, skill sets, and perspectives	When doing group work, set aside time for students to discuss their respective backgrounds, majors, career goals, and approaches to problem solving.

Table 7 is not intended as a comprehensive list; it provides sample activities that could be implemented without major structural changes to curricula. For example, a shared laboratory report rubric could be implemented in first-year biology and chemistry lab classes that is based on the Claim, Evidence, Reasoning model (Model Teaching, 2019). We often see that students get confused by different lab report formats in biology and chemistry lab classes. This approach would not only help our students in a particular discipline, but would demonstrate that the same communication skills are used in different disciplines. For Quantitative Reasoning, a common set of data can be plotted and discussed in the three disciplines, emphasizing different aspects of the same exercise in each area. In Table 7, we also suggest the use of common rubrics for oral and written communication, some examples of which can be found on the American Association of Colleges and Universities website (AAC&U, 2023).

3. Conclusion

3.1. Purposes of the Guiding Documents

The three guiding documents for biology, chemistry, and mathematics were developed for different purposes. Despite the abundant intersections of scientific skills and disciplinary practices among these disciplines, the intrinsic differences in the goals of the guiding documents challenged our analysis and alignment of SS & DP among disciplines. For chemistry, the guiding document, ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs, (American Chemical Society Committee on Professional Training, 2015) emphasizes content, skills and competencies that are required and recommended for ACS accreditation of undergraduate programs. Thus, the itemization is granular and focused on the chemistry discipline and its various subdisciplines. In contrast, the guiding documents for both biology and mathematics were not developed as guides for creating accredited undergraduate programs. The mathematics guiding document, A Common Vision for Undergraduate Mathematical Sciences Programs in 2025 (Saxe & Braddy, 2015), contains skills and competencies for students studying mathematics that are important for professional success, and describes how mathematics is useful to other disciplines. Both the chemistry and mathematics guiding documents were written by each discipline's professional organization (ACS and Mathematical Association of America, respectively). The biology guiding document, Vision and Change in Undergraduate Biology Education: A Call to Action (Bauerle et al., 2011), was authored by a larger umbrella organization, the American Association for the Advancement of Science (AAAS). It takes a 'view from above' approach and discusses general skills and competencies rather than discipline-specific content. There is no discussion or comparison of individual biology subdisciplines, which differs from chemistry. The biology guiding document emphasizes the promotion and implementation of meaningful change in biology undergraduate education at different scales, from the classroom level to the university level, to mobilize stakeholders and find support for teaching and training faculty.

Identifying and articulating commonalities across these three STEM disciplines (biology, chemistry and mathematics) has the potential to impact the most science undergraduate students early in their education. The majority of biology and pre-health majors at both two-year and four-year institutions take chemistry, biology, and mathematics in their first year. STEM students will be positively impacted by articulation of common SS & DP in introductory STEM courses. Students can struggle to connect ideas or transpose knowledge between disciplines when students are not made explicitly aware of the commonalities of SS & DP in STEM. (Martin-Hansen, 2018; Momsen et al., 2010) The commonalities discussed in this paper are points of potential leverage if a common language is to be developed and employed by professors in all three disciplines. Better alignment among introductory classes in different disciplines will help students connect the classes into an integrated whole, potentially improving student performance, and will help students to see that seemingly separate STEM classes actually emphasize similar skills. In addition, by highlighting commonalities with other disciplines, collaborative multidisciplinary teams in biology, mathematics, and chemistry will not have to go through the same detailed analysis of these guiding documents to improve interdisciplinarity in their classrooms. Additionally, having a comparison of guiding documents may make professors more aware of guiding documents in their own discipline as well as others. As Mulnix & Vandegrift, noted in 2014 there was a lack of awareness in Biology as well as the other STEM disciplines of the existence of the Vision and Change guiding document. Overall, having explicit and common SS & DP in courses from different disciplines will enhance student preparation for inter- or multidisciplinary learning and promote research and professional success.

3.2. Better Prepare Students for Educational and Professional Transitions

Alignment of course curricula across biology, chemistry, and mathematics using identified commonalities will ease transitions such as changing academic majors within STEM, the transfer of students from two-year to four-year institutions, and movement from college into the workplace. When students switch majors or transfer from two- to four-year institutions, the scientific skills are transferable due to the common disciplinary practices. Common SS & DPs drawn from the Guiding Documents will clear up confusion when different disciplines use different labels for these skills and practices. Faculty can ease these transitions by emphasizing the commonalities. These skills are valued in professional settings and this work will provide students with the language to express what skills and practices they possess.

3.3. Foster Multidisciplinarity in Student Success

The alignment of scientific skills and disciplinary practices creates a scaffold or guide for faculty across biology, chemistry, and mathematics to emphasize and teach these skills and practices. Faculty can use this guide to see commonalities across the disciplines and to reinforce these SS & DP in different courses. This document provides a common language across the disciplines which allows for a bridging between the traditional disciplinary silos (Reinholz & Andrews, 2019), and faculty can refer to the language of the different disciplines in their classes. The suggestions listed in Table 7 can be used as a starting point for this process. For example, interdisciplinary resources for instructors of introductory biology, chemistry, and mathematics can be developed and made available for use. While these guiding documents may lack the specific scientific concepts that are taught in introductory courses, the practices and skills can be considered universal. This alignment of scientific skills and disciplinary practices can be used by faculty and departments to come together to create institutional change.

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