Guidance: Curriculum Development and Refinement Rubric

Preparing students to be contributors to the development of more sustainable chemicals or products requires traditional chemistry competencies related to making observations, explaining phenomena, and drawing scientific conclusions. In addition to the fundamentals, students need experience making decisions where they assess trade-offs, anticipate consequences, and optimize the impact-benefit ratio,[1] all within a life cycle and systems thinking context. This approach to practicing chemistry that considers the broader implications of chemicals throughout their life cycle, and on various systems, is referred to herein as *green and sustainable chemistry.*

Green and sustainable chemistry principles and practices provide a framework for chemists to extend the scope beyond the laboratory benchtop and consider the life cycle impacts of chemicals before and after they are in a reaction flask. This broadened lens illuminates key interactions between chemicals and people, the economy and/or the environment. In addition, green and sustainable chemistry principles and practices are associated with citizen attitudes consistent with sustainable action and motivation to act responsibly and ethically toward all inhabitants of the Earth. So much of sustainability is underpinned by chemical systems, and it is essential that chemists are trained to think about ways to leverage their expertise to address grand challenges, such as those identified in the UN Sustainable Development Goals. Teaching chemistry from this systems perspective will require most chemistry educators to learn a new vocabulary and concepts. While elements of systems thinking such as boundary conditions, scale, feedback loops, etc. are sometimes implicit in chemistry lessons, their presence is not explicitly discussed. Therefore, much of the focus of this project will be on creating education materials that include systems thinking concepts and skills.

This rubric will be used to assess curriculum developer's modules that integrate green and sustainable chemistry into the undergraduate chemistry curriculum. The rubric builds upon an original assessment methodology created by the Interdisciplinary Teaching about Earth for a Sustainable Future (InTeGrate) project team.[2] InTeGrate is an NSF-funded STEP Center grant for geoscience education. InTeGrate is being used as a template because it is seen as a successful model for ensuring the development of an open access repository of high-quality sustainability-related education materials. Herein, we have developed a rubric to ensure modules meet the broad goals of the project and guidelines for best practices in curriculum development. Module evaluation is divided into six sub-areas: guiding principles, learning objectives and goals, assessment and measurement, resources and materials, instructional strategies for learning, and alignment (Figure 1).

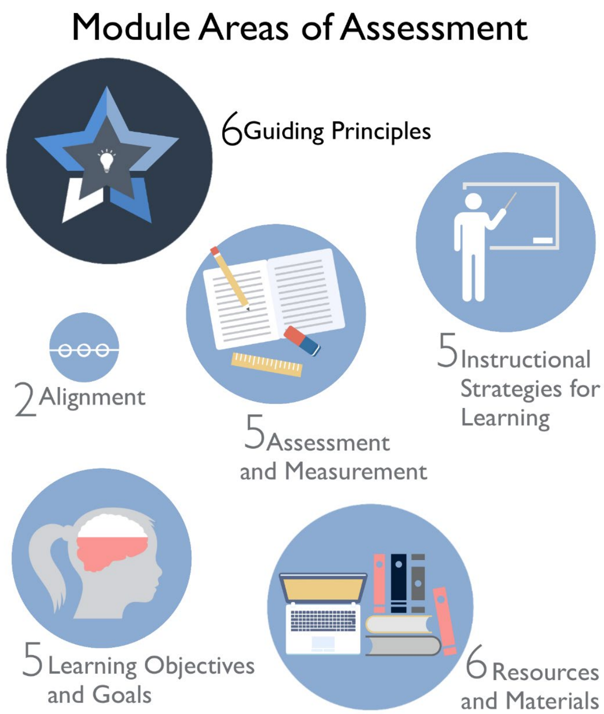

Figure 1. Six sub-areas of module evaluation and the number of evaluation elements contained in each area. A perfect score must be obtained for the six guiding principle elements, while a score of ≥ 83% is sufficient for the other areas.

The six sub-areas have a total of 29 elements that are equally weighted at 3 points each and are evaluated using the following scoring scheme:

- **3 points**: rubric element explicitly and/or pervasively addressed in module materials
- **2 points**: rubric element addressed in majority of the module materials
- **1 points**: rubric element addressed in some of the module materials
- **0 points**: rubric element not addressed in the module materials

For a module to be approved, a score of 18/18 must be achieved on the guiding principles portion of the rubric. Scores of 83% or higher must be achieved in each of the other sub-areas of the materials rubric. Materials meeting the above criteria will earn a minimum score of 77/87.

Guiding Principles (must score 18/18)

1 **Module incorporates one or more sustainability grand challenges facing society**: Grand challenges include resource issues (e.g., minerals, energy, water, food, etc.) and environmental issues (e.g., climate change, hazards, waste disposal, environmental degradation, environmental health). The UN Sustainable Development Goals list specific grand challenges that need addressing and can serve as a guide for helping chemists frame a problem.[3–5] In addition, the UN SDGs highlight the need to address inequalities among marginalized or disadvantaged groups. Therefore, modules should support inclusivity and equity in the classroom and in the design of chemical solutions and problem-solving in diverse societies.

2 **Module develops student ability to address interdisciplinary problems**: Interdisciplinary problems require diverse perspectives that promote understanding of the interactions between environmental, economic, and societal issues. Such materials integrate robust chemical science with trans-disciplinary knowledge from other disciplines such as engineering, biology, social sciences and humanities. Materials should seek opportunities to introduce interdisciplinary ways to address chemistry problems (e.g., a biologically mediated chemical synthesis pathway).

3 **Module improves student ability to practice *green and sustainable chemistry*:** Modules should help students understand the potential and responsibility chemists have in reducing the environmental, safety and health impacts of chemistry across the life cycle. Students should learn that chemists make significant choices about chemicals and synthetic processes that impact sustainability and performance. Curricular content should incorporate *green and sustainable chemistry* ideas and practices that are aligned with traditional disciplinary core ideas (as articulated in the guiding principles document).

4 **Module develops/refines the skills students need to practice science and engineering:** Science and engineering practices are essential to the successful application of *green and sustainable chemistry* that requires: complex problem solving, managing uncertainty, and flexibility when dealing with changing data, interpretations and constraints. Key science and engineering practices for chemistry include: asking questions and defining problems, carrying out investigations, analyzing data and constructing models and explanations, designing solutions, pursuing evidence-based explanations and arguments for chemical phenomena, and communicating scientific information.[6] *Designing solutions* is especially pertinent for chemistry students to understand as they learn how to design syntheses of chemicals and materials, evaluate those production methods, assess disposal impacts, and consider the benefits and impacts of such chemicals to society, the economy and the environment. Modules should enable students to develop and refine the skills necessary to implement these practices.

5 **Module makes use of authentic and credible chemical data to learn central chemistry concepts in the context of scientific methods of inquiry**: Curricular materials use the most appropriate data available for the topics under discussion. Data should be backed by

reproducible and robust experimental methods. If controversial data or data interpretations are intentionally introduced reflecting, for example, prevailing societal concerns, they must be clearly noted as such and compared to credible data. References to updated data sources will be provided as available.

6 **Module incorporates systems thinking**: Module develops students' ability and propensity to consider the systems in which chemicals exist and how they interact with natural and human systems. Modules should develop students' abilities to identify and work with systems. While lower-division modules may focus on defining systems vocabulary and having students examine simplified systems, upper-division modules should have students engage in systems thinking for chemicals in realistic scenarios. Ultimately, the aim is for senior chemistry students to have the skills to perform independent literature research and evaluate chemicals through a systems lens. To build these skills, many lower-division modules should incorporate foundational systems thinking terms and concepts; there will be repetition between modules so it should be noted that certain units are optional if already performed during a previous module.

Learning Objectives and Goals (must score 13/15)

7 **Learning objectives describe measurable chemistry education goals:** Learning objectives are clear statements that describe the desired goals of the instruction. These should be decided upon prior to module development so that the module structure can be reverse designed to meet these overarching outcomes. The objectives and goals are directly linked to the ideas published in the guiding principles document. Learning objectives should directly state specific competencies (consistent with the green and sustainable core competencies), skills and/or knowledge that students are to master or demonstrate. When appropriate, learning objectives should require integration of multiple chemistry concepts that reflects analysis in authentic contexts outside the classroom.

8 **Instructions and/or rubrics provide guidance for how students meet learning goals**: Rubrics are developed that provide the student a clear indication of the performance conditions and standards necessary to meet learning goals. If this specificity is not possible (e.g. internal cognition, affective changes), metrics used to measure indications of such change must be described for the student.

9 **Learning objectives and goals are appropriate for the intended use of the module**: Broadly, modules should address content mastery, critical thinking skills, and core learning skills related to introducing guiding principles. The way in which students are expected to demonstrate such skills will vary between modules, but specific, measurable, performance expectations should be clearly stated within the modules. All modules should focus on helping students to navigate the complexity of systems, with the specific examples tailored according to

student experience level (*e.g.*, second-semester organic chemistry modules consider an increased number of components and more system-system interactions compared to introductory general chemistry modules).

10 **Learning objectives and goals are clearly stated for the module in language suitable for the level of the students**: Learning objectives and goals should avoid jargon and highly technical language unless required.

11 **Learning objectives and goals demonstrate the process and nature of science, and help students' development of scientific habits of mind**: The process of science and scientific inquiry (or habits of mind) include the notions that science demands evidence, science is a blend of logic and imagination, science explains and predicts, scientists attempt to avoid bias, and there are accepted criteria for evaluating the credibility of data. The nature of science includes such attributes as: the world is understandable, recognizing the difference between credible and non-credible scientific arguments, scientific ideas are subject to change, scientific knowledge is long-lasting or durable but subject to change and science cannot answer all questions. Scientific habits of mind include recognition that science is a complex social activity, science is organized by disciplines and carried out at multiple institutions, there are accepted ethical principles related to the conduct of science, scientists participate in public affairs as specialists and citizens, scientists communicate their understanding of the world to multiple audiences, and that there are accepted criteria for evaluating the credibility of scientific interpretations and scientific claims.[7] Similarly, six engineering habits of mind have been developed to reflect essential disciplinary ways of thinking: systems thinking, creativity, optimism, collaboration, communication, and ethical considerations. [8] Since engineering is solutions focused, and chemists not only analyze scientific data but also design and implement solutions, chemistry education should be including these habits of mind as well. Specifically, systems thinking and ethical considerations are essential components of *green and sustainable chemistry*, thus highlighting the need for an interdisciplinary approach to chemistry education.

Assessment and Measurement (must score 13/15)

12 **Assessments align with learning goals and module activities**: Formative assessments and summative assessments will be embedded to determine the extent to which students have met the module goals. Modules should be structured around core ideas, rather than granular details, to help students develop a connected set of ideas to explain chemical phenomena.[9] Every assignment and activity should link directly to the goals assessed. Resources needed for activities and assessments are clearly stated.

13 **Assessments are criterion referenced**: Assessments include a clear and meaningful list of criteria used to evaluate student work and participation including all the information students

need to know how a grade will be calculated. This could be accomplished with a formal rubric or with a more informally structured description of what each grade looks like. This could involve a rubric for each type of assignment, a list of criteria and associated point values for specific assignments or a sample of acceptable or unacceptable student work such as examples of excellent or poor papers or projects.

14 **Assessments are sequenced, varied and appropriate to the content**: The sequence and schedule or pace of the assessments match the content. Assessments should vary in type and duration and can build on previously acquired knowledge within the course or in prerequisite courses.

15 **Assessments address goals at successively more demanding cognitive levels**: Assessments should be designed to give students opportunities to demonstrate their thinking at varying levels of complexity. As students progress, assessments should explore students' ability to integrate understanding, practice, and ways of reasoning in authentic contexts. Module developers don't have to use any particular task categorization framework but should be intentional in the design of varied assessment questions/assignments making sure some items involve deep thinking. A science-specific framework exists for ranking the cognitive demand and necessary integration of practices and skills that a given task contains.[10,11] Educators are likely already familiar with Bloom's taxonomy where skills can be categorized by complexity;[12] Bloom's Taxonomy Action Verbs can be referenced to help categorization of a specific task, though in practice there is often overlap.[13]

16 **Assessments require students to describe strategies and tools for performing objective scientific evaluations**: Assessments seek out opportunities for students to practice systematic, multi-criteria decision-making. As appropriate, modules should assess if students understand basic principles of multi-criteria decision-making (e.g., trade-offs, alternatives assessments, and impact-benefit ratio) and provide scenarios for students to practice decision making that is justified with scientific evidence and incorporates a systems perspective.

Resources and Materials (must score 15/18)

17 **Instructional materials contribute to the stated learning objectives and are thoughtfully selected**: Module materials such as textbooks, monographs, articles, lecture notes, environmental health and safety literature, audio or video recordings, games, or websites should directly support one or more guiding principles or core concepts embedded in learning objectives and goals. Module supporting content should be as easily accessible and low cost as possible to minimize logistical and economic barriers for module adoption.

18 **Students will recognize the link between the learning objectives, goals and the learning materials**: Curriculum should be designed such that students can recognize the purpose

of all content, materials, resources, technologies, and instructional methods used in the module; how each resource helps them achieve the stated learning goals; and which materials are required, and which are recommended resources. Module reviewers will assess whether they believe the students will understand how to use the materials provided.

19 **Instructional materials should be sufficiently diverse and at the depth necessary for students to achieve learning objectives and goals**: Instructors should provide meaningful content using a variety of sources (e.g., text, articles, presentations, websites, lecture notes, outlines, and multimedia). The level of detail in supporting materials is appropriate for the level of the course and it is at sufficient depth for students to achieve the learning goals.

20 **Materials are appropriately cited**: All learning materials, software and learning resources must conform to copyright law and proper citation protocols unless there is a specific statement attached to the materials stating that they are in the public domain.

21 **Instructional materials include examples of chemistry content in a sustainability context**: In addition to foundational chemistry content, the materials include recent research that places the content in a sustainability context.

22 **Instructional materials and the technology to support these materials are clearly stated**: If specific technology is needed, requirements are clearly stated, *e.g.,* computer lab with licenses to a specific software application.

Instructional Strategies for Learning (must score 13/15)

23 **Learning strategies and activities support stated learning objectives and goals**: The learning activities promote the achievement of the stated learning objectives and goals. Students should be able to meet the stated objectives and goals using the learning activities provided. Activities should be designed to support reinforcement and mastery in multiple ways.

24 **Learning strategies and activities promote student engagement with the materials.** Activities should provide multiple opportunities to facilitate students' understanding and mastery of the learning objectives and goals. Activities should be designed to be inclusive by keeping in mind the range of student experiences and learning styles within a diverse classroom. Teaching methods should respect the diverse group of students in the classroom by utilizing the range of talents and experiences they bring, avoiding assumptions about students, and including various perspectives. Activities should foster instructor-student, content-student, and student-student interactions where appropriate. Examples include group discussions or blogs, small-group projects, peer critiques or rotating assigned communication roles such as moderator or summarizer. Activities should be designed to motivate students by demonstrating the task value (e.g., showing that the content is interesting and important), connecting to personal experiences, and/or building on what they know and addressing their initial beliefs.[14,15]

Engagement strategies should aim to incorporate societal, economic, and political contexts. Instructors should model the use of inclusive language that respects student gender, racial and cultural identities.

25 **Learning activities develop student metacognition**: Students should reflect on their thinking; they should understand *how and why* a task is performed, rather than only the cognition to perform the task. The distinction between metacognition and cognition is important for developing students' higher order thinking skills such as posing questions, problem-solving or deepening mechanistic-reasoning for different topics in chemistry. Activities should provide opportunities for students to monitor and evaluate their learning process.[16] Activities should include an appropriate balance of guidance versus exploration and opportunities for reflection, iteration, discussion, and synthesis. Students should be able to assess their own learning and confirm they are on the right track. For particularly challenging or novel concepts, educators should facilitate metacognitive assessments or monitoring to help identify specific areas where student thinking processes need further development or intervention.

26 **Learning strategies and activities provide opportunities for students to practice communicating about chemistry and chemical phenomena**: Students will be engaged in independent thinking, problem solving, and communicating their understanding to others. Activities should challenge misconceptions and provide opportunities for students to practice judging what constitutes credible evidence. Activities should allow students to practice communicating their thinking to the teacher, but also to their peers, allowing for formative feedback and coaching that helps advance student learning. Peer-to-peer feedback can foster an educational environmental in which all student voices and ideas can be shared and help construct collective understandings.

27 **Learning strategies and activities scaffold learning of foundational chemical ideas**: Activities should promote deep learning by stimulating student intellectual growth from novice to more advanced levels. Activities should be structured to allow students to first note obvious connections and then grasp the significance of those connections. At higher levels, students should be challenged to appreciate the significance of the parts as related to the larger concept and eventually extend those concepts to general principles outside the discipline.

Alignment (must score 5/6)

28 **Teaching materials, assessments, resources and learning activities align with one another**: A constructive alignment approach suggests that goals, learning activities and assessments within each section of the module align with one another and directly with stated learning objectives and goals. A curriculum map that identifies core skills and content, learning strategies and resources can be used as an effective way to ensure alignment.

29 **All aspects of the module are aligned**: An alignment approach suggests that curricular materials align directly with stated module goals holistically across the entire module.

References:

(1) Gilbertson, L. M.; Zimmerman, J. B.; Plata, D. L.; Hutchison, J. E.; Anastas, P. T. Designing Nanomaterials to Maximize Performance and Minimize Undesirable Implications Guided by the Principles of Green Chemistry. *Chem. Soc. Rev.* **2015**, *44*, 5758–5777.

(2) Science Education Resource Center at Carleton College. InTeGrate- Interdisciplinary Teaching about Earth for a Sustainable Future https://serc.carleton.edu/integrate/ (accessed May 18, 2020).

(3) Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. The Role of Chemistry in Inventing a Sustainable Future. *Nat. Chem.* **2015**, *7*, 941–943.

(4) ACS. Chemistry & Sustainable Development Goals https://www.acs.org/content/acs/en/sustainability/chemistry-sustainable-development-goals.html (accessed May 11, 2020).

(5) Mahaffy, P. G.; Matlin, S. A.; Whalen, J. M.; Holme, T. A. Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking. *J. Chem. Educ.* **2019**, *96*, 2730–2741.

(6) National Science Teaching Association. NGSS- Science and Engineering Practices https://ngss.nsta.org/PracticesFull.aspx (accessed May 18, 2020).

(7) American Association for the Advancement of Science. *Science for All Americans*; 1st ed.; Oxford University Press: New York, 1991.

(8) Katehi, L.; Pearson, G.; Feder, M. The Status and Nature of K–12 Engineering Education in the United States. *Bridg. K-12 Eng. Educ.* **2009**, *39*, 5–10.

(9) Cooper, M. M.; Posey, L. A.; Underwood, S. M. Core Ideas and Topics: Building Up or Drilling Down? *J. Chem. Educ.* **2017**, *94*, 541–548.

(10) Moon, A.; Stanford, C.; Cole, R.; Towns, M. Analysis of Inquiry Materials to Explain Complexity of Chemical Reasoning in Physical Chemistry Students' Argumentation. *J. Res. Sci. Teach.* **2017**, *54*, 1322–1346.

(11) Tekkumru-Kisa, M.; Stein, M. K.; Schunn, C. A Framework for Analyzing Cognitive Demand and Content-Practices Integration: Task Analysis Guide in Science. *J. Res. Sci. Teach.* **2015**, *52*, 659–685.

(12) Adams, N. E. Bloom's Taxonomy of Cognitive Learning Objectives. *J. Med. Libr. Assoc.* **2015**, *103*, 152–153.

(13) Armstrong, P. Bloom's Taxonomy https://programs.caringsafely.org/wp-content/uploads/2019/05/Caring-Safely-Professional-Program-Course-Development.pdf.

(14) González, A.; Paoloni, P. V. Perceived Autonomy-Support, Expectancy, Value,

Metacognitive Strategies and Performance in Chemistry: A Structural Equation Model in Undergraduates. *Chem. Educ. Res. Pract.* **2015**, *16*, 640–653.

(15) Pintrich, P. R. The Role of Motivation in Promoting and Sustaining Self-Regulated Learning. *Int. J. Educ. Res.* **1999**, *31*, 459–470.

(16) Cooper, M. M.; Sandi-Urena, S.; Stevens, R. Reliable Multi Method Assessment of Metacognition Use in Chemistry Problem Solving. *Chem. Educ. Res. Pract.* **2008**, *9*, 18–24.