Process for Creating General Chemistry Performance Expectations

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Introduction

General chemistry occupies an essential part of many students college-level work in chemistry, whether or not they are majoring in the chemical sciences. However, there has been little work done to bring general chemistry courses to the point where they align with extensive recent work in K-12 standards and the requirements for further study, or reflect how students learn and how teaching is changing in the 21st century. At the Spring 2015 ACS National Meeting, the Society Committee on Education (SOCED) and the Executive Committee of the Division of Chemical Education (DivCHED) discussed addressing these gaps by creating general chemistry performance expectations. They appointed a joint task force, which has engaged in several months of discussion about how this could be done, summarized here. Briefly, the task force members, recognizing that the purposes and locations of general chemistry courses are diverse, envision a distributed process based on many campuses to provide empirical basis for any consensus building. To do this well would entail a four-to-five year process including a planning year, a year of preparatory work at each site, and then at least two years of work to implement the performance expectations at each site, including time for revisions.

Performance Expectations: A Brief Overview

Performance expectations, as noted in the National Research Council's *Framework for K-12 Science Education* ("*Framework,*" NRC 2012), are "statements that describe activities and outcomes that students are expected to achieve in order to demonstrate their ability to understand and apply the knowledge described in…disciplinary core ideas." Such statements, supported by work to identify core ideas and practices for general chemistry, would provide chemistry programs with guidance about what is considered most important in contemporary chemistry, including prerequisite knowledge for a rich program of foundational and advanced study in chemistry. Hence, well-done performance expectations are a means to increase the rigor of general chemistry courses, supporting students in learning chemistry knowledge in authentic, practice-oriented perspectives. They also have a role in supporting closer alignment of course design, instruction, and assessment. Performance expectations would also increase the articulation of general chemistry courses with new state standards in K-12 science (many of which are drawn from the *Next Generation Science Standards, NGSS)*, with the needs of students in programs and majors that require chemistry, and with the competency-focused redesign of the MCAT exam. It is important to note that performance expectations are not lists of topics or items for assessment. Rather, their multi-dimensional nature requires careful review of the content and the goals of general chemistry so that students are able to use their knowledge in rich, authentic activities that reflect the actual use of chemistry knowledge in a variety of settings. Their use requires a series of shifts in instructional practice. Hence, SOCED and DivCHED empaneled a joint task force to describe a process for creating these expectations.

The task force has discussed several different models by which performance expectations can be created. It reflected on the ways this has been done within the NRC *Framework*, the College Board's support documents for Advanced Placement tests in science (College Board), the curriculum-wide treatment of undergraduate biology within the AAAS/ NSF-supported *Vision and Change in Undergraduate Biology* (AAAS), and recent examples of reform in undergraduate science, including the process followed by the faculty at Michigan State University (Cooper, *et al.)* as part of their AAU-supported course reform (AAU). This prior work provides examples of what performance expectations would look like, including a sense of the grain size required for them: not a detailed list of topics or specific learning objectives, but also not something which simply points to concepts or practices in the abstract. Rather, performance expectations are formulated in a way that reflect an underlying understanding of the components of a course or curriculum that are put together in a way that it can be seen how student performance, not abstract terms like "knowledge" or "understanding," is foregrounded. Examples of these are now available, and in Appendix A we present one set of high school NGSS statements—here in the area of chemical reactions—that show the combination of the *Framework*'s dimensions: Disciplinary Core Ideas (in orange), Science and Engineering Practices (in blue), and Crosscutting Concepts (in green). In Appendix B we also offer prominent examples from the work recently done at Michigan State University to create performance expectations for general chemistry at that campus.

Foundational core for general chemistry performance expectations

The general chemistry performance expectations developed by the proposed process should have a foundational core that parallels the three dimensions of the NRC *Framework for K-12 Science Education*, itself the foundational core of the performance expectations for the *Next Generation Science Standards*. However, the NRC *Framework* dimensions should not simply be used in their current form. After all, they were developed for a project working within all K-12 science. However, the success of those dimensions as a foundational core of performance expectations for the NGSS strongly argues that general chemistry performance expectations should be built on a similar scaffold, with components that reflect:

(a) A well-structured set of **major ideas** describing the content of general chemistry, based on a deeply-rooted coherent conceptual set (likely a progression) within the course. The ideas are concepts that reflect the science of chemistry—not a list of topics and not with a specified order;
(b) Actual **practices** within the chemical sciences that will serve as both a learning outcome themselves and as a basis for the learning process for the students; and
(c) A set of clear, meaningful **cross-curricula connections** to other aspects of undergraduate chemistry curricula and also to other disciplines and professional settings where a knowledge of chemistry is essential.

Once available, these components are then used as the foundational core for writing actual performance expectations. As indicated earlier, the 'grain size' of these performance expectations are not at the level of a particular list for a particular course. Rather, they represent well-structured statements of expectations that, if met, can ensure that students can perform in a way that reflects mastery of the major ideas, practices, and connections expected for successful students in a particular general chemistry setting.

Because these performance expectations are for a college entry-level course, it will be important to indicate what prior knowledge and skills are assumed—or at least, hoped-for—when students start general chemistry. This would cover chemistry, other sciences, mathematics, and skills in argumentation. A working understanding of particular concepts will be important. Models for such expectations are available in the AP course materials and in the NGSS.

Source materials

The task force identified several different possible source materials for this work. The processes used for the "reinvention" of the Advanced Placement science exams, for the revision of the MCAT, and for the design and implementation of the NGSS are all recent and highly relevant examples. As to the content of the new performance expectations, particular attention should be paid to efforts currently underway within college science—in chemistry (AAU; Cooper, *et al.*), in biology (AAU; AAAS/NSF Vision and Change), and in relation to the new MCAT (NEXUS project, which is a model of how different campus teams were guided through a process of coordinated course reform by Howard Hughes Medical Institute)—that involve faculty working on campus-specific answers to the challenge of multi-dimensional learning in college science. Similarly, the chemistry education community also has available the resource of the Anchoring Concepts Content Maps (AACM) project. Developed with an historical approach, the ACCM is also something being used to consider how to integrate practices and to support faculty in reflection on their instruction and assessment (see references in Murphy, *et al.*). The ACCM project has also extended to specific areas of chemistry, such as organic and physical chemistry, and those materials will be helpful in documenting how later courses may align with and build upon earlier chemistry courses (Holme and Murphy, Murphy *et al.*, Raker *et al.*, Zenisky and Murphy).

Process: Distributed, but coordinated work on multiple campuses

A consistent theme in our discussions was the challenge of creating a set of performance expectations that were useful for different settings of general chemistry courses. These performance expectations need to work well for course design, faculty professional development, and student learning in different places. As a result, we are certain that, to be successful, the performance expectations cannot be imposed from outside. On the other hand, chaos will result if the process just suggests that different campuses work independently of one another. Therefore, we propose that an optimal route for the creation of performance expectations is to use a distributed but coordinated process on multiple campuses, coordinated by a single entity with adequate staff support. In this regard, we note that the process by which the ACCM materials were developed is a good example of a distributed process that may be helpful here (Zenisky and Murphy).

The process we envision would involve convening a set of faculty from particular sites—perhaps four-to-six—to support them in designing performance expectations for general chemistry at their own settings. The faculty from the different sites would receive a common introduction to some major framing ideas, including the multi-component nature of performance expectations, published resources about course content and science practices, an understanding of the current research on student learning in college, and information on the interaction of instruction and assessment in learning and course development. They would then separately work to create a set of major ideas, practices, and cross-curricula connections—the foundational core of the performance expectations for their courses. These components would be compared across sites and refined. A consensus would be sought, but not forced. Faculty at specific sites will then carry forth with the writing of performance expectations for their settings, indicating how the different components contribute to the expectations, how the expectations can shape an instructional sequence to support a learning progression and each individual component, and how assessment will support learning and also reveal student understandings for formative and summative purposes.

The different sites will also be supported in collecting data on both their own experience as faculty and, of course, on the work that their students do in learning with these performance expectations. This data will be both a basis of further revision and also a key part of the sharing of ideas with other campuses.

The process will conclude with the different sites working together to produce a flexible but consistent vision of performance expectations that can serve as a foundational core for a range of general chemistry courses. Once this is done, they will then consider if an overarching consensus can be reached on a set of performance expectations that serves multiple settings well. If a consensus is not a reasonable outcome, then the larger group will instead produce a document that suggests how individual campuses can adapt one or more of the examples for local use.

The process will need to embrace the central role of assessment at multiple levels. There should be a clear plan for using the performance expectations to obtain information on success for students. Because well-written performance expectations reflect multiple components of student outcomes—ideas, practices, and connections—they can demonstrate how students have become proficient in understanding and using chemical knowledge in important ways. They can capture student growth from their initial understandings to a later point that approaches mastery, documenting how students have become more competent with their knowledge over time.

Performance expectations and corresponding assessments will also provide vital information on aspects beyond student outcomes. This includes the role of prior preparation, the success of implementation at a given site, and the new ways that students are mastering chemistry knowledge. Reflecting on the detailed information obtained from assessments also provides evidence that will be the basis of course revisions and for further course development. All of this will contribute to an iterative process at each site and should support good practices for program assessment as expected by the ACS Committee on Professional Training and accrediting agencies. Finally, given the needs for reflective revision at each site and to provide a solid basis for dissemination of evidence based practice, the process should include a strong research component. This would serve the formative needs of the campuses (for their students and their practice).

Support and time line for the process

The large scope of the project means it requires substantial logistic and financial support at each site. An early part of the process will be to specify the level of support for each site and who will provide that support. For that reason, it may be prudent to begin with a planning grant within which many of the process details can be developed. The logical places for this are the National Science Foundation or the FIPSE program at the U.S. Department of Education.

There are several ways that the American Chemical Society can contribute to this effort. It is, of course, the premier organization to support chemical education. Therefore, it should be engaged in its role to support chemistry educators as they share research and ideas. In addition, its national reach and prominent position mean ACS may also be able to serve a key organizational role for this effort, for example by serving as the host and coordinator for cross-campus work and communication and, ultimately, providing a venue through which key outcomes are disseminated. This could occur with outcomes such as an empirically-grounded foundational core for performance expectations at all types of campuses and, if available, a consensus set of performance expectations. Further documentation would include specific, campus-level examples and a well-described set of processes and tools for faculty work. Finally, given the need for financial support, ACS could serve as the grantee for coordinated work.

Given these different ideas, the task force envisions a four-to-five year time line for the work. This would entail a planning year, a year of preparatory work at each site, and then at least two years of work to implement the performance expectations at each site, including time for revisions. We note that there are several examples for this, including the Undergraduate STEM Education Initiative supported by AAU (Cooper et al.), the implementation of STEM education centers by APLU, the NEXUS effort for revision of courses aligned to the new MCAT by Howard Hughes Medical Institute, and efforts such as the "Partnership for Undergraduate Life Science Education" that followed on the AAAS / NSF *Vision and Change* process. Funding support could be sought from the NSF, perhaps beginning with a request for a conference grant for a workshop where the group that will do further planning can review the previous work, consider examples in more depth, and map out more details for implementing the process.

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NEXT GENERATION SCIENCE STANDARDS For States, By States

HS.Chemical Reactions

Students who demonstrate understanding can:

HS-PS1-2. **Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties.** [Clarification Statement: Examples of chemical reactions could include the reaction of sodium and chlorine, of carbon and oxygen, or of carbon and hydrogen.] [*Assessment Boundary: Assessment is limited to chemical reactions involving main group elements and combustion reactions.*]

HS-PS1-4. **Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.** [Clarification Statement: Emphasis is on the idea that a chemical reaction is a system that affects the energy change. Examples of models could include molecular-level drawings and diagrams of reactions, graphs showing the relative energies of reactants and products, and representations showing energy is conserved.] [*Assessment Boundary: Assessment does not include calculating the total bond energy changes during a chemical reaction from the bond energies of reactants and products.*]

HS-PS1-5. **Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs.** [Clarification Statement: Emphasis is on student reasoning that focuses on the number and energy of collisions between molecules.] [*Assessment Boundary: Assessment is limited to simple reactions in which there are only two reactants; evidence from temperature, concentration, and rate data; and qualitative relationships between rate and temperature.*]

HS-PS1-6. **Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium.*** [Clarification Statement: Emphasis is on the application of Le Chatelier's Principle and on refining designs of chemical reaction systems, including descriptions of the connection between changes made at the macroscopic level and what happens at the molecular level. Examples of designs could include different ways to increase product formation including adding reactants or removing products.] [*Assessment Boundary: Assessment is limited to specifying the change in only one variable at a time. Assessment does not include calculating equilibrium constants and concentrations.*]

HS-PS1-7. **Use mathematical representations to support the claim that atoms, and therefore mass, are conserved during a chemical reaction.** [Clarification Statement: Emphasis is on using mathematical ideas to communicate the proportional relationships between masses of atoms in the reactants and the products, and the translation of these relationships to the macroscopic scale using the mole as the conversion from the atomic to the macroscopic scale. Emphasis is on assessing students' use of mathematical thinking and not on memorization and rote application of problem-solving techniques.] [*Assessment Boundary: Assessment does not include complex chemical reactions.*]

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Developing and Using Models
Modeling in 9–12 builds on K–8 and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.
- Develop a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-PS1-4)

Using Mathematics and Computational Thinking
Mathematical and computational thinking at the 9–12 level builds on K–8 and progresses to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.
- Use mathematical representations of phenomena to support claims. (HS-PS1-7)

Constructing Explanations and Designing Solutions
Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.

Disciplinary Core Ideas

PS1.A: Structure and Properties of Matter
- The periodic table orders elements horizontally by the number of protons in the atom's nucleus and places those with similar chemical properties in columns. The repeating patterns of this table reflect patterns of outer electron states. (HS-PS1-1) *(Note: This Disciplinary Core Idea is also addressed by HS-PS1-1.)*
- A stable molecule has less energy than the same set of atoms separated; one must provide at least this energy in order to take the molecule apart. (HS-PS1-4)

PS1.B: Chemical Reactions
- Chemical processes, their rates, and whether or not energy is stored or released can be understood in terms of the collisions of molecules and the rearrangements of atoms into new molecules, with consequent changes in the sum of all bond energies in the set of molecules that are matched by changes in kinetic energy. (HS-PS1-4),(HS-PS1-5)
- In many situations, a dynamic and condition-dependent balance between a reaction and the reverse reaction determines the numbers of all types of molecules present. (HS-PS1-6)
- The fact that atoms are conserved, together with knowledge of the chemical properties of the elements involved, can be used to describe and predict chemical reactions. (HS-PS1-2), (HS-PS1-7)

Crosscutting Concepts

Patterns
- Different patterns may be observed at each of the scales at which a system is studied and can provide evidence for causality in explanations of phenomena. (HS-PS1-2),(HS-PS1-5)

Energy and Matter
- The total amount of energy and matter in closed systems is conserved. (HS-PS1-7)
- Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-PS1-4)

Stability and Change
- Much of science deals with constructing explanations of how things change and how they remain stable. (HS-PS1-6)

Connections to Nature of Science

Scientific Knowledge Assumes an Order and Consistency in Natural Systems
- Science assumes the universe is a vast single system in which basic laws are consistent. (HS-PS1-7)

• Apply scientific principles and evidence to provide an explanation of phenomena and solve design problems, taking into account possible unanticipated effects. (HS-PS1-5) • Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources (including students' own investigations, models, theories, simulations, peer review) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future. (HS-PS1-2) • Refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. (HS-PS1-6)	**ETS1.C: Optimizing the Design Solution** • Criteria may need to be broken down into simpler ones that can be approached systematically, and decisions about the priority of certain criteria over others (trade-offs) may be needed. *(secondary to HS-PS1-6)*	

Connections to other DCIs in this grade-band:
HS.PS3.A (HS-PS1-4),(HS-PS1-5); **HS.PS3.B** (HS-PS1-4),(HS-PS1-6),(HS-PS1-7); **HS.PS3.D** (HS-PS1-4); **HS.LS1.C** (HS-PS1-2),(HS-PS1-4),(HS-PS1-7); **HS.LS2.B** (HS-PS1-7); **HS.ESS2.C** (HS-PS1-2)

Articulation of DCIs across grade-bands:
MS.PS1.A (HS-PS1-2),(HS-PS1-4),(HS-PS1-5),(HS-PS1-7); **MS.PS1.B** (HS-PS1-2),(HS-PS1-4),(HS-PS1-5),(HS-PS1-6),(HS-PS1-7); **MS.PS2.B** (HS-PS1-3),(HS-PS1-4),(HS-PS1-5); **MS.PS3.A** (HS-PS1-5); **MS.PS3.B** (HS-PS1-5); **MS.PS3.D** (HS-PS1-4); **MS.LS1.C** (HS-PS1-4),(HS-PS1-7); **MS.LS2.B** (HS-PS1-7); **MS.ESS2.A** (HS-PS1-7)

Common Core State Standards Connections:
ELA/Literacy -

RST.11-12.1	Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account. (HS-PS1-5)
WHST.9-12.2	Write informative/explanatory texts, including the narration of historical events, scientific procedures/ experiments, or technical processes. (HS-PS1-2), *(HS-PS1-5)*
WHST.9-12.5	Develop and strengthen writing as needed by planning, revising, editing, rewriting, or trying a new approach, focusing on addressing what is most significant for a specific purpose and audience. (HS-PS1-2)
WHST.9-12.7	Conduct short as well as more sustained research projects to answer a question (including a self-generated question) or solve a problem; narrow or broaden the inquiry when appropriate; synthesize multiple sources on the subject, demonstrating understanding of the subject under investigation. *(HS-PS1-6)*
SL.11-12.5	Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest. *(HS-PS1-4)*

Mathematics -

MP.2	Reason abstractly and quantitatively. (HS-PS1-5),(HS-PS1-7)
MP.4	Model with mathematics. *(HS-PS1-4)*
HSN-Q.A.1	Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays. (HS-PS1-2),*(HS-PS1-4),(HS-PS1-5)*,(HS-PS1-7)
HSN-Q.A.2	Define appropriate quantities for the purpose of descriptive modeling. (HS-PS1-4),*(HS-PS1-7)*
HSN-Q.A.3	Choose a level of accuracy appropriate to limitations on measurement when reporting quantities. *(HS-PS1-2),(HS-PS1-3),(HS-PS1-4),(HS-PS1-5),(HS-PS1-7)*

* The performance expectations marked with an asterisk integrate traditional science content with engineering through a Practice or Disciplinary Core Idea.

http://nextgenscience.org/hsps-cr-chemical-reactions

Appendix B. Examples of Performance Expectations for General Chemistry*

Example	Scientific Practice(s)	Disciplinary Core Idea(s)	Cross-Cutting Concept(s)
Construct an explanation to discuss both how and why the patterns in periodic trends (such as atomic radius, ionization energy, electronegativity) change both down a group and across a row in the periodic table.	Constructing an explanation	Forces and interactions	Patterns; cause and effect
Construct a model and use it to explain how and why the temperature changes when a salt dissolves in water.	Constructing a model	Energy changes (macro, molecular); forces and interactions	Cause and effect
Design a substance with a molecular structure with a given set of properties.	Designing solutions	Structure properties	Structure function
Construct a model and use it to explain how and why carbon dioxide acts as a greenhouse gas.	Constructing a model	Structure properties; energy (quantum)	Cause and effect; energy transfer; conservation

*Developed at Michigan State University