9

Do Real Work, Not Homework

Brian P. Coppola

9.1

Thinking About Real Work

9.1.1

Defining Real Work: Authentic Learning Experiences

In his 1997 essay, “Situated Cognition and How to Overcome It,” Carl Bereiter [1] uses the fictionalized experiences of two students, Flora and Dora, to make an important and often-repeated point about learning. Both of these students pass the same Algebra I course with flying colors. But in Algebra II, while Flora continues her success, Dora barely passes. Bereiter’s point is that in Flora’s case, she actually learned the mathematics of algebra in her Algebra I class, and so she could transfer (transport) this learning to Algebra II. Dora, it is supposed, did not *learn algebra*, but *learned about doing algebra problems*, and succeeded in Algebra I through rote repetition and recognition.

Many versions of the Flora/Dora story have featured in discussions of science learning, where contrast is made between *meaningful learning* and *rote learning* [2, 3], or the distinction between *learning about science*, *learning science,* and *learning to be a scientist* is emphasized [4]. Unlike a traditional apprenticeship, where one learns specific artisanship in a materially relevant setting under the direction of a master craftsperson, school learning is distilled, abstracted, and idealized, with the validation of correct answers standing in as the nearly universal indicator of learning. Even at the introductory college level, there is compelling evidence that students can produce or select the proper answer in a way that is disconnected from a deep understanding of the underlying subject matter [5–10].

As one proceeds in higher education, it becomes increasingly more likely that science instructors are skilled in the art of their specific discipline-centered subject, and so the chances increase that the limitations and basis for this knowledge will feature more prominently than it might have at the introductory level, and that science-related values, such as skepticism, are appended to the lessons [11]. Yet, the main experience students have, even in upper level science classes, is the

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canonized textbook, its in-text homework exercises, and the sort of testing that allows both the Floras and the Doras to do well.

Over in the School of Art and Design, things are different. Here, the work is automatically more authentic: drawing, painting, and sculpting classes result in artifacts that can be scrutinized by practitioners for their direct, real-world merit, as does public performance of dance, music, or theater. While there is no guarantee that each student taking classes in the arts is investing the same level of purpose, meaning, emotion, and experience in conveying a story that others can or will reflect upon, *learning to be an artist* in a standard art class, through the production of and conversation about art [12], is a more likely outcome than *learning to be a scientist* is in a standard science class.

Stein *et al.* have reviewed the use of the authentic learning experiences in the context of university-level instruction [13]. They have synthesized a definition of authentic classroom practice (p. 241) as "that which reflects, for the students, a combination of personal meaning and purposefulness within an appropriate social and disciplinary framework. The learning experience is authentic for the learner while simultaneously being authentic to a community of practice." The key features embedded here are (i) work that matters outside the context of an assignment whose sole outcome is allocating course points (i.e., a painting is hung in a gallery for contemplation and reflection by observers) and (ii) work that is new, and not derivative or replicative, and which can be treated as any other work created by one who is practiced in the art (i.e., spectroscopic data collected on a purified product from a reaction that has never been carried out previously).

Herrington has contributed significantly to the development and identification of useful design elements for authentic tasks [14] as well as the instructional design to support authentic learning [15], in which "learners must be engaged in an inventive and realistic task that provides opportunities for complex collaborative activities" [16, p. 1]. Herrington's catalog of design elements derives from a variety of researchers and theorists (Table 9.1), and is neutral to the mode of delivery, instead focusing on concrete analytical features that can be easily assessed.

Lombardi has also reviewed the use of the term "authentic learning" [40], and contributes to placing it into the larger context of real classrooms, and how changing one element (e.g., student roles) will necessarily cascade throughout the entire learning environment (e.g., learning goals, instructor roles, content, assessment). Intentional and deliberate change in one part of a complex, interlocked system with lots of moving parts requires corresponding changes in expectations, performance, training, and support in the other components. The rapid emergence and proliferation of new in-class and online instructional methods has disrupted, in many cases, what Elmore calls the "instructional core" [41] and can result in fragmentation and incoherence in the learning environment [42–44].

In his seminal review, "Academic Work," Doyle [45] covers the research in which the nature of an academic task dictates or even predicts the corresponding academic performance (p. 165).

"A comparison of memory and comprehension tasks suggests that preparation suitable for one type may not necessarily be suitable for the other. Accomplishing

Table 9.1 Design elements for authentic learning tasks.

Real-world relevance	Authentic activities match the real-world tasks of professionals in practice as nearly as possible. Learning rises to the level of authenticity when it asks students to work actively with abstract concepts, facts, and formulae inside a realistic – and highly social – context mimicking "the ordinary practices of the (disciplinary) culture" [17–25]
Ill-defined problem	Challenges cannot be solved easily by the application of an existing algorithm; instead, authentic activities are relatively undefined and open to multiple interpretations, requiring students to identify for themselves the tasks and subtasks needed to complete the major task [25–27]
Sustained investigation	Problems cannot be solved in a matter of minutes or even hours. Instead, authentic activities comprise complex tasks to be investigated by students over a sustained period of time, requiring significant investment of time and intellectual resources [18, 26–28]
Multiple sources and perspectives	Learners are not given a list of resources. Authentic activities provide the opportunity for students to examine the task from a variety of theoretical and practical perspectives, using a variety of resources, and requires students to distinguish relevant from irrelevant information in the process [22, 27–29]
Collaboration	Success is not achievable by an individual learner working alone. Authentic activities make collaboration integral to the task, both within the course and in the real world [22, 26, 30]
Reflection (metacognition)	Authentic activities enable learners to make choices and reflect on their learning, both individually and as a team or community [22, 30, 31]
Interdisciplinary perspective	Relevance is not confined to a single domain or subject matter specialization. Instead, authentic activities have consequences that extend beyond a particular discipline, encouraging students to adopt diverse roles, and think in interdisciplinary terms [18, 32]
Integrated assessment	Assessment is not merely summative in authentic activities but is woven seamlessly into the major task in a manner that reflects real-world evaluation processes [33–35]
Polished products	Conclusions are not merely exercises or substeps in preparation for something else. Authentic activities culminate in the creation of a whole product, valuable in its own right [30, 36, 37]
Multiple interpretations and outcomes	Rather than yielding a single correct answer obtained by the application of rules and procedures, authentic activities allow for diverse interpretations and competing solutions [27, 32, 37–39]

Adapted from Ref. [14]. by Jan Herrington, with permission from Jan Herrington.

a comprehension task can, because of the effects of semantic integration, interfere with the ability to reproduce specific facts or the surface features of the original text. On the other hand, accomplishing a memory task can produce knowledge in a form that is not easily applied to recognizing new instances or making inferences to new situations. Thus, reading for comprehension may be inappropriate for a recall task. It is probably for this reason that students typically adjust study strategies to fit the nature of the test they expect to take. A parallel argument can be made for procedural and comprehension tasks. Learning to use an algorithm does not necessarily enable one to understand why the algorithm works or when to use it. Similarly, learning to understand why an algorithm works or when it should be used does not necessarily lead to computational proficiency."

Bereiter supposes that Dora has approached her learning of Algebra I as an example of what Doyle calls "school work" [1] (memory, recall, algorithm), while Flora, in the same classroom situation, made the connection to "real life" needs (building on prior knowledge, application, evaluation). In Algebra I, both of these strategies worked; in Algebra II, they did not. To be clear: Doyle would argue that Flora is also using memorization and recall because these "school work" strategies accomplish different things than the "real life" strategies, and what she may have is a better metacognitive sense of how to manage and decide what to do and when. An underlying challenge in teaching is how to design instructional tasks to elicit and support the decisions Flora made about her learning, and how to keep those made by Dora from succeeding, even in the short term, and even if and when they have been successful in the past.

In their 1990 book *Teaching Writing that Works*, Rabkin and Smith [46] contrast explicitly different instructional strategies and associated student behaviors they have observed in English composition classes, and provide strong and practical recommendations that reflect nearly all of Herrington's design elements for authentic learning. The key underpinning of their approach is to put every aspect of writing, as is true for any of us who write for any reason whatsoever, into a larger social and intellectual context. Writing results from a negotiated understanding, within student groups, of purpose, meaning, and audience, and it improves through evaluation, editing, and feedback that are as critical for students to give, as they are to receive. Rabkin and Smith summarize their approach in the clear and concisely stated principle "real work is better than home work" (p. 159), which Rabkin has further elaborated [47], and which has inspired the title for this chapter.

9.1.2
Doing Real Work: Situated Learning

From a science education perspective, the Dora/Flora problem often appears when thinking about laboratory instruction. There is a core belief that students are not *doing science*, and are only *learning about science*, if they do not participate in experimental design, data collection, data analysis, and other components of experimental laboratory science. The influential arguments for this position come from Gabel [48], Lunetta [49], and Hofstein [50].

From a theoretical perspective, situated cognition provides a convincing framework for understanding how *thinking like a scientist* is coupled with the social settings in which science is done, or situated [237]. Sweeney and Paradis [51, p. 195] assert that "students are unable to fully appreciate the scientific method and the essence of scientific inquiry unless they have the opportunity to acquire and analyze data first-hand." They contend that the fundamental postulate of situated cognition theory [17], that knowing and doing cannot be separated, is key to the design of science learning environments.

Critics insist that the locus of control of cognition is in the mind-brain [52] and not the physical setting where the brain happens to be located. They argue for context as a necessary but insufficient feature to understanding learning. Bereiter [1] appeals to the community to overcome its obsession with situated cognition because, after all, both Flora and Dora were in exactly the same situation but their learning outcomes were divergent. A more moderate view integrates these positions by pointing out that a setting, such as a research laboratory, reflects an environment in which situated cognition theory is fruitful for understanding scientific practices and the production of knowledge (i.e., you are less likely to learn it in the kitchen), and "follows the literature in terms of communities of practice, cognitive apprenticeship, scaffolded learning, affordances, constraints, and the production of valued products, through a social epistemology" [53] and where the "agency and intention of people" matter (p. 310). In fact, Bereiter agrees with the importance of teaching intentionality [54].

Historically, the rhetoric of situated learning followed on the heels of situated cognition. In reflecting on the development of her ideas on situated learning [55], Lave also "take[s] issue with … work characterized [using either/or characterizations of learning], for it either maintains overly simple boundaries between the individual (and this is the "cognitive") and some version of a world "out there," or turns into a radical constructivist view … Learning, it seems to me, is neither wholly subjective not fully encompassed in social interaction, and it is not constituted separately from the social world (with its own structures and meanings) of which it is part" [56, p. 64].

Situated learning theory was the foundation for the development of authentic learning pedagogy. Prior to her development of the design elements for authentic learning environments [14], Herrington was interested in the critical characteristics of situated learning [57], particularly regarding electronic media: "computer-based applications are a further step removed from real life work situations, and criticisms have been leveled at computer-based materials that claim to use a situated learning framework in their design." Herrington's list of design elements for authentic learning [57] aligns with features of McLellan's elements of situated learning [237], and with the later work on authentic tasks [14]. In addition, there is substantial correspondence with Rabkin's notion of "Real Work" in designing writing assignments (Table 9.2).

Table 9.2 Alignment of design elements for situated learning (1997) versus authentic learning (2000), authetnic tasks (2004) and real work (1990).

Situated learning [237]	Authentic learning [57]	Authentic tasks [14]	Real work [46]
	Authentic context	Real-world relevance	Purpose
	Authentic activities	Ill-defined problem	
		Sustained investigation	
Multiple perspectives	Multiple perspectives	Multiple sources and perspectives	Audience
Collaboration	Collaborative construction of knowledge	Collaboration	Collaboration
Reflection	Reflection	Reflection (metacognition)	Editing and feedback
	Authentic assessment	Integrated assessment	Integrated assessment
Cognitive apprenticeship	Access to expert performance and models		
Coaching	Coaching and scaffolding		
Articulation of learning skills, Stories	Articulation		Making meaning
		Interdisciplinary perspective	
		Polished products	Polished products
		Multiple interpretations and outcomes	
Technology			

Since the early 1990s, my collaborators and I have been interested in designing chemistry learning environments that feature many of the elements present in both authentic and situated learning, and at looking at others' work through this lens. We adopted Rabkin's *Real Work* rhetoric because of its intuitive appeal.

Our inspiration for thinking about *Real Work* in undergraduate chemistry instruction derives from the studio instruction model that dominates the visual and performance arts, where young painters learn to paint and young dancers learn to dance. Our focus, however, was not in the laboratory, where this translation is most easily made (*young researchers learn to research*), but rather in the classroom setting, where learning canonical facts contained in canonical textbooks (or videos) still dominates.

When art students get an assignment, they generate and create, bringing about new objects and interpretations of the world; when science students get an assignment, it is usually a problem set with a fixed set of prescribed answers. There are benefits and strengths resulting from both kinds of assignments, and the translation from science to art was obvious: reproducing a faithful copy of a master's existing work is the classic apprenticeship model. There are things to be learned by getting the right answer, mainly gauging one's own performance against a clear set of standards.

Translating from art to science, on the other hand, is reminiscent of C. P. Snow's [58] famous phrase "The Two Cultures," in which he describes the inability of scientists and non-scientists to communicate, and that to do so required bridging "a gulf of mutual incomprehension" (p. 4). Beginning in the 1990s, engineering programs began integrating didactic instruction with design and fabrication activities in the same space, and adopted the term "studio instruction" to characterize this change [59]. In 1993, Wilson adapted this to physics instruction [60], and by1999 a few chemistry departments, particularly those located at the polytechnic universities where the studio engineering classrooms had been invented, had begun to experiment with the integrated lab–lecture format [61, 62].

Studio instruction is a powerful metaphor for education because it not only changes how students carry out their assignments but also changes what the assignments are. For decades, reform in science education has placed its strongest emphasis on *how* students do their assignments rather than any fundamental re-imagining of *what* assignments they are doing. The rhetoric surrounding these reforms emphasizes adjectives about the type of learning that is intended, which is in turn used to describe the pedagogical methods: conceptual, student-centered, algorithmic, problem-based, team-based, creative, peer-led [63]. An examination of the assignments given to students reveals a uniform culture of "problems and exercises" with "solutions" and pedagogies that seek to move the students more efficiently and productively toward the correct answer.

In developing our ideas about *Real Work*, we were not interested in criticizing or abandoning goals such as "getting to the right answer" as a part of learning science. Instead, we wanted to develop a way of broadening the landscape of student assignments in the sciences, to examine the value-added benefits, and to give others a useful way of thinking about their own work. In doing so, we have identified six attributes that derive or align strongly from the areas of authentic and situated learning, and which have provided particularly good entrees for work in introductory undergraduate chemistry education (Table 9.3).

9.2
Attributes of Real Work

9.2.1
Balance Convergent and Divergent Tasks

There is a historical tendency to see classroom teaching and learning in the sciences and the arts as fundamentally different because of Snow's cultural divide. Assignments and tasks in the arts are creative, generating new artifacts that express individual values, background, experience, and perspective. Students

Table 9.3 Attributes for *Real Work* assignments.

Balance convergent and divergent tasks	Convergent tasks are evaluated against a given standard (or “the right answer”) and so learners can assess how successful a given pathway is in achieving the prescribed goal. Divergent tasks focus on the construction of individual outcomes within a set of common guidelines, and so individual learners come to a defensible position
Peer presentations, review, and critique	Developing explanatory knowledge allows learners to deepen their understanding and to anticipate arguments, revealing strengths and weaknesses in understanding
Balance teamwork and individual work	Successful communities of practice rely on individual members with a diverse base on knowledge and experiences, and where, in the aggregate, a common understanding encompasses more than any individual might have achieved
Students use the instructional technologies	As a matter of principle, learners should be trained in at least the instructional technologies deemed useful by a teacher. It is often more informative to see what learners construct in representing their understanding using multiple modes than for the learners to see only the practiced, expert view
Use authentic texts and evidence	Understanding and interpreting empirical evidence can be accomplished by direct experimentation, and also by using the original primary literature. Parts of these resources will be inaccessible to new learners, but other parts will not be (alternatively, significant historical papers can be used)
As important to the class as the teacher’s work	The work generated by students, resulting from divergent tasks, in particular, can be returned to the class as student-generated instructional materials. Subsequent assignments and/or testing based on student-generated materials explicitly distributes the role of “teacher” in the instructional setting

in science classes learn the facts, and how to be encultured by them, against a background of “right answers” and “wrong answers.” There is also a historical tendency, in science education [64], to create false dichotomies when an advocate for one position wants to highlight his or her point of view: content *versus* process, lecture *versus* discussion, facts versus concepts. Lave’s commentary (see above) on not treating situated cognition as an either/or proposition is an appeal to reject a false dichotomy.

Comparing assignments and tasks in the arts and sciences is more a matter of traditional emphasis than an intrinsic difference in the disciplines. Assignments in the arts can certainly be intended to get a student to compare his or her work against a fixed standard (e.g., making a faithful copy of another work), as clearly as assignments in the sciences can generate new artifacts (e.g., research carried out on an undergraduate thesis project). A useful way to understand this comparison is found in the classic attributes of creativity: convergent and divergent thinking.

Over 60 years ago, Guilford introduced the concepts of convergent and divergent thinking [65, 66], and these ideas have proved to be robust, as they continue to be used and studied, including by neuroscientists who observe differences in brain activity based on differences in tasks, and who contend that these ways of thinking may indeed be separate and distinct [67–70]. Convergent thinking, as the name implies, relies on taking prior knowledge and an understanding of existing standards to generate the single best ("accurate") answer in a speedy and logical manner. Divergent thinking, which also relies of one's existing skills and experience, generates as many possible contextually meaningful answers as possible, relying on fluidly lateral rather than linearly vertical reasoning [71]. Straker and Rawlinson [72] provide a balanced view on these different parts of a creative process that resonates strongly with scientific practices: divergent thinking produces multiple and varied interpretations (or hypotheses) which can then be subjected to a convergent analysis in order to narrow the field of options to a few, or perhaps the single best defensible one, in order to carry a plan forward. The principles of divergence and convergence are widespread. In statistics, for instance, data modeling can randomly produce observable data over a distribution of outcomes (called a *generative model*), or narrowly define an outcome according to constraints or conditions (called a *discriminative model*), combining which, according to Bishop and Lasserre, results in "the best of both worlds" [73].

Both convergent and divergent design strategies can be used for student assignments, each to a different end. Convergent assignments produce work that is measured against an externally prescribed outcome and against a predefined standard of practice. These assignments are designed for learners to encounter the most commonly anticipated errors made by novices, and provide ways for learners to self-monitor and self-regulate their progress by understanding how their work compares with the prescribed standard, not only in its final form but also in the process, or pathway, used to get there. The benefit derived from well-designed convergent assignments is in making explicit as many of the implicit pitfalls typically associated with learning the lessons.

Divergent assignments produce work that is measured against the community of practice into which the work, thus produced, can be evaluated for its fit. Divergent assignments are open enough for learners to encounter errors that, in general, will require the use of standards such as comparison with others' work, debate, justification, and defensibility in order to identify, refine, and understand the choices made in the production of the work. The benefit derived from well-designed divergent assignments is that contributions made to the community of understanding broadens the community itself, and through comparison and debate of these contributions promotes a deep and reflective understanding of the lessons.

Poorly designed convergent assignments have been a target for criticism. If the single correct answer can be produced, or selected, by simple decoding or pattern recognition, without needing to follow a pathway in which the learner engages the underlying ideas, then two things happen: (i) getting the right answer for the wrong reason creates a sense of false confidence in the learner that productive learning is taking place [74] and (ii) the learning that does occur is indistinguishable from nonsense [75]. The benefit derived from any of the active learning classroom strategies [76] is to focus explicit attention on the steps in the path in order to promote better understanding of the basic ideas, and upon which improved test performance (converging on the single, right answer), the ubiquitous metric for evaluating these strategies, is the outcome [77]. The challenge for researchers in fixed-response methods of assessment is that the pathway is inferred: there is no direct evidence to differentiate Flora's deeper understanding of the subject from Dora's improved test-taking skills [78].

9.2.1.1 **Convergent Assignments**

Convergent tasks can be both generative and creative. In organic chemistry, an excellent example of a well-designed convergent assignment can be found in spectroscopic identification of molecular structure. Although there is a single best answer to the question of "what is the structure of this compound," everyone, from a seasoned experimentalist to a first-year undergraduate, has to deal with the same sources of data in order to answer the question. Structure determination, by its nature, is a convergent task: there is a structure; the work is to figure out what it is. Figure 9.1 illustrates the sort of experimental data that one might commonly encounter in such a problem. There is no single, prescribed path from these data to the structural solution that the character in the figure is thinking about. Teaching structural determination is challenging precisely because it defies prescribed algorithmic thinking.

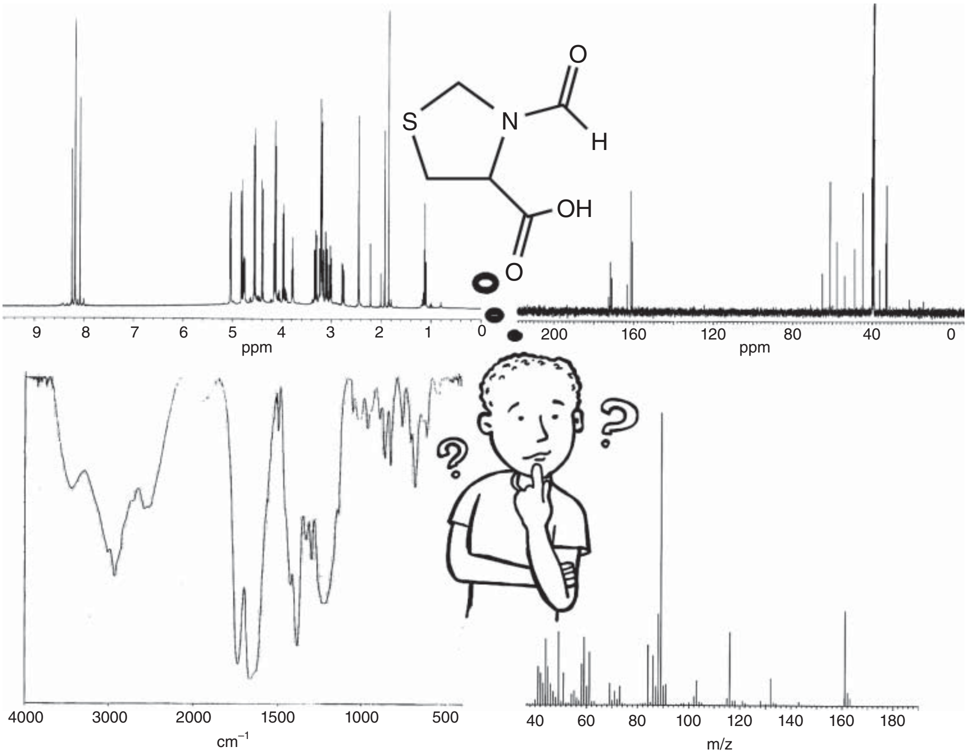


Figure 9.1 A typically good convergent assignment: a structure determination problem.

9.2.1.2 Divergent Assignments

First-year organic chemistry students also encounter divergent assignments. These are equally challenging to both teach and learn. Perhaps the most common example of a well-designed divergent assignment in organic chemistry is retrosynthetic analysis [79]. The starting point for retrosynthetic analysis is a molecular structure. The task is to take your existing knowledge of chemical reactions, including constraints derived from experimental design, and to construct as many different rational pathways as you can think of that will result in this molecular structure. Experimental constraints might include the availability of certain chemical substances you require, the compatibility of different components in the system, the likelihood for alternate reaction pathways that will reduce the production of this target substance, and the ease with which those by-products might be separated from the desired product. Figure 9.2 gives a simple example of a retrosynthetic analysis for an example target molecule. Unless the person who proposes these pathways has specific knowledge of these exact experiments having been performed, the only way to truly differentiate among them is by carrying out the experiments. However, an important decision made by an experimentalist is a convergent one: which pathway is deemed to be the most likely to succeed, and why? This decision is often a topic of heated debate between students and their advisors, between faculty members whose research groups are competing to get to the same finish line, and between individuals on a National Science Foundation review panel, who might debate who deserves a better score on their research proposal.

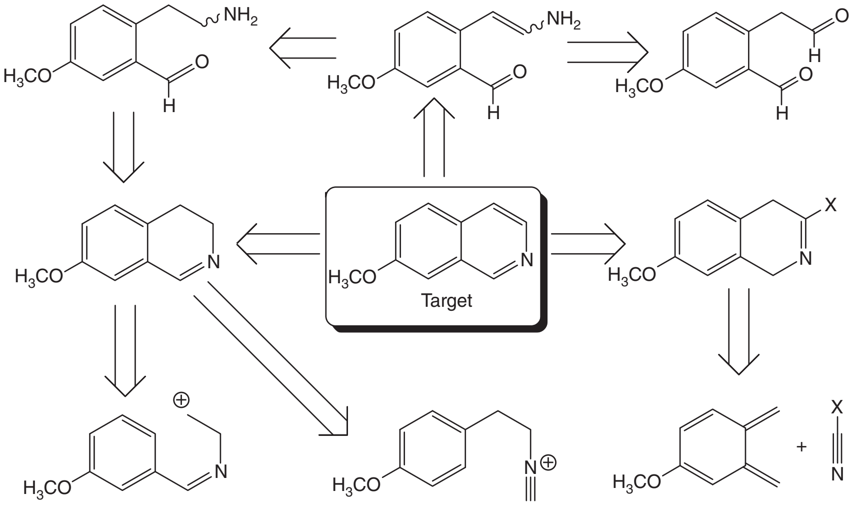
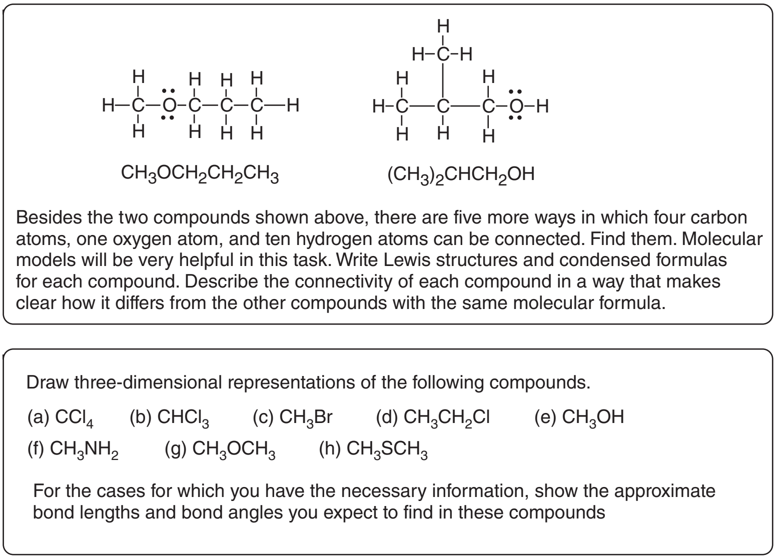


Figure 9.2 A typically good divergent assignment: retrosynthetic analysis.



$CH_3OCH_2CH_2CH_3$

$(CH_3)_2CHCH_2OH$

Besides the two compounds shown above, there are five more ways in which four carbon atoms, one oxygen atom, and ten hydrogen atoms can be connected. Find them. Molecular models will be very helpful in this task. Write Lewis structures and condensed formulas for each compound. Describe the connectivity of each compound in a way that makes clear how it differs from the other compounds with the same molecular formula.

Draw three-dimensional representations of the following compounds.

(a) CCl_4 (b) $CHCl_3$ (c) CH_3Br (d) CH_3CH_2Cl (e) CH_3OH

(f) CH_3NH_2 (g) CH_3OCH_3 (h) CH_3SCH_3

For the cases for which you have the necessary information, show the approximate bond lengths and bond angles you expect to find in these compounds

Figure 9.3 Examples of convergent textbook problems.

9.2.1.3 Balancing Convergent and Divergent Assignments

During the first few weeks of an organic chemistry class, students encounter many convergent textbook exercises related to the basics of molecular structure and the relationship between structure and reactivity (Figure 9.3) [80, pp. 11, 25].

In 1994, in our supplemental instruction program, called Structured Study Groups, we used divergent task design as the core of what we called a *studio format*, which was intended to be more like the classroom design for a drawing class than for fabricating artifacts in an engineering program [81–83]. For their first (divergent) studio assignment, students select from a list of recent chemistry journals, each one getting a unique combination of title and year. After thumbing through the journals to find a molecule with between 10 and 13 carbon atoms, the students are asked to (i) construct (draw) five new rational molecular structures with the same molecular formula as the one they found, (ii) rank the molecules based on selected properties (e.g., magnitude of dipole moment, boiling point, and solubility), and (iii) write out the rationales for their rankings.

The likelihood that two students will find molecules with the same molecular formula is, effectively, zero, and the number of possible drawings (rational plus irrational) they might make is, effectively, infinite. All the students are working in the same task, where collaboration and conversation about strategy is useful and encouraged, and almost nothing short of someone else doing your work for you is going to be the way to shortcut the process. Note that task (ii) has no known reliable solution. Although students learn some general trends about these properties using simple examples, the sorts of molecules being drawn in this assignment still defy the best predictive theories.

There is no solution to converge to. Unless the experimental results are known over this entirely imagined series of molecules, the best answer is a combination of (i) extrapolating a set of simple principles to these complex cases and (ii) arriving at the most defensible answer. Students bring their written-out assignments to the 2-h studio session and, under the guidance of their leader (an upper level undergraduate), participate in a structured round of peer review and critique (see below). After the review process, the students get back their work (along with the comments – it is not a grading process) and the experience of having participated in this hour-long discussion, and they then decide whether or not there is something about their work they want to revise; they always do.

Each week, there is a divergent assignment that becomes the main topic of discussion and debate during the subsequent session. Some of these assignments include the following, over the course of the year:

1) Finding an example of a given type of reaction from a journal article and reformulating it as a quiz question [84];
2) Writing essays in response to the need for introducing the formal study of research ethics in science classes, and eventually writing their own case studies [85];
3) In a term-long project during the second semester, working in teams of three to four to transform an individual segment of a journal article into a fairly detailed print and Web-based resource [86].

In all these cases, the design follows the generalization of Straker and Rawlinson [72] for creative work: an initial divergent (or generative) phase to sample the diverse options derived from individual character, background, and experience, followed by a convergent (or discriminative) phase, in which some sense of community and/or disciplinary standards are applied to sort through and understand how (or even whether) the different options might be evaluated.

9.2.1.4 **Convergent Assignments in Team Learning**

Convergent assignments, idealized by a "problem set," can be done in isolation, referencing only an authority ("the answer key"), and reveal information about the pathway (decision-making process) taken to solve the problem only by inference. Discussion or recitation periods can help uncover some of the implicit decisions that arise during problem solving, as can modeling help the thinking process by an instructor's thinking out loud. An excellent contribution of the Peer-Led Team Learning (PLTL) [87] model to teaching has been to structure small group discussion around the problem-solving process, making it an explicit topic of discussion. The PLTL strategy, in working with challenging convergent problems, sets a six- to eight-person threshold for the group size, finding that more than this makes a productive discussion more difficult.

Although it is tempting to have access to the authoritative answer, either in the form of an answer key or an individual – study group leader or faculty member – who acts as a living answer key, there is robust literature on the value of error making in learning [88, 89], on the value of difficult and challenging problems [90], and an emergent understanding that easy access to authoritative answers can lead to a psychological state of self-deception [91], wherein a learner confuses understanding someone else's answer with having understood the process by which it was constructed.

9.2.1.5 **Divergent Assignments in Team Learning**

Divergent assignments, by their nature, require larger groups to produce an array of different outcomes, with a structure that allows time for analysis, debate, and defense of those outcomes. In our divergent studio assignments, we have found that between 18 and 22 students is ideal, perhaps because it allows for enough diversity in the collective work of the group, and enough examples to begin to see recurring themes in the analysis of the outcomes.

Using divergent assignments is a useful teaching tool for training peer facilitators. Each term, the Science Learning Center at the University of Michigan runs the peer-led study group (PLSG) program, where small groups of 8–10 undergraduates taking various introductory science classes are matched with an upper level undergraduate student who serves as the group facilitator. Upwards of 60–70% of any given class participate in these groups. As a part of their training, the nearly 80–90 facilitators for the organic chemistry classes meet once a week, in their own small groups, with a graduate student instructor. Each week, as a way for them to review and think about the variation in organic chemistry, they bring their solutions to a set of divergent problems to their session with the graduate instructor. The facilitators, after having to write out or post their solutions to the tasks, are guided by the graduate instructor in a discussion about the relevant subject matter, the "party-line" for how certain topics are treated by the department's faculty, and the pit falls and recurring problems that students have with the given topics. A sampling of these tasks is provided in Table 9.4.

There is no argument that supports pitting convergent and divergent design against each other. Both designs have unique strengths, and should be used together. The challenge for convergent design is to create problems that avoid the "unfortunate coincidence," where the correct answer can easily result from the wrong pathway [92, 93]. A supportive pedagogical design (e.g., PLTL) can intervene by giving students a chance to make thinking about their pathways more explicit. The challenge for divergent design is to create a group context where there is enough pedagogical confidence and expertise to deal with the diversity of potential solutions while at the same time finding the commonalities among them, particularly where breadth and depth of subject matter knowledge are needed to compare and evaluate a large collection of student work.

Real Work uses a balance of convergent and divergent tasks because creativity is a core value which combines the ability to think openly and laterally of options, without constraint, with the ability to evaluate, rank, and defend those options according to rational criteria.

Table 9.4 Divergent tasks for training organic chemistry peer facilitators.

Week 1	*Discussion topics*
Draw a rational molecular structure with the molecular formula $C_{15}H_{16}N_2O_3$	Line abbreviation representations Formal charges Hybridization, electronic, and observable geometries Predicting and evaluating resonance contributors 3D orbital drawings for substructures
Week 2	*Discussion topics*
Using a pK_a table, construct a diprotic acid that would have different structures in solutions of pH 1, 7, and 12	Identify and estimate the ratio of species in solution Identify a base that could completely mono-deprotonate the most acidic form, but not fully deprotonate anything else, even in excess Identify a base that could completely mono-deprotonate the most acidic form and fully deprotonate any other acidic functions if used in excess pH versus pK_a Estimating pK_a values from representative examples
Week 4	*Discussion topics*
Create and name a molecule with the molecular formula $C_7H_{13}BrO_2$. Select a nontrivial bond and draw a Newman projection for its most stable conformation	Identifying gauche, syn, and anti relationships Translating between 3D drawings and Newman projections Evaluating attractive and repulsive forces (steric, electrostatic, H-bonds) Identifying equivalent sets of hydrogen and carbons atoms for NMR spectroscopy Nomenclature
Week 7	*Discussion topics*
Prepare responses to a student who asks	Reach consensus on the responses In class: Given $C_8H_{13}Br$. Draw a molecule that meets these criteria; show the mechanism

(continued overleaf)

Table 9.4 (*Continued*)

a) What are structural isomers? b) What is the relationship between these two structures? c) How to predict the expected reaction product(s) in substitution and elimination reactions? d) How to identify mechanistic pathway from the product(s) of a reaction?	a) Can undergo one S_N2 reaction, demonstrates inversion of configuration using lithium azide b) Can undergo an E2 reaction with sodium ethoxide and gives exactly three different alkene products c) Can form a resonance-stabilized carbocation when heated in water, resulting in a racemic mixture of substitution products along with some elimination products d) Is a trans di-substituted cyclohexane that can undergo an SN2 reaction with sodium cyanide to give a cis isomer e) Cannot undergo an S_N2 reaction with anything, but can undergo an E2 reaction with a strong base in order to produce an allene ($R_2C{=}C{=}CR_2$) f) Cannot undergo S_N or E reactions g) For part (a), what happens if you treat your molecular with potassium *tert*-butoxide? h) For part (b), what happens is you heat your molecule with ethanol? i) For part (c), what happens if you treat your molecule with sodium acetate? j) For part (d), what happens if you treat your molecule with sodium ethoxide?

9.2.2
Peer Presentations, Review, and Critique

Peer-led teaching, learning, and assessment are currently well-established strategies in higher education [94–101], although they are processes that have also fallen in and out of favor for 2000 years [102]. In the first major review of this area, Goldschmid and Goldschmid [96] hypothesized that the most recent interest in teacher-directed peer-to-peer work, which started in the 1960s, was a practical response to the growth of university class sizes and the concomitant concern that students were becoming more passive in their role as learners. As Topping observes [100], early programs emulated the traditional classroom structure, where the tutor was seen as a surrogate or extension of the primary instructor. In their meta-study on the skills of peers relative to faculty instructors [99], Falchikov and Goldfish found that peer and teacher assessment generally resembled each other, particularly when the criteria being used were clear and explicit, and, consistent with this, that upper level undergraduates were no better than beginners.

Over the past 60 years, the interest in moving away from replicating didactic instruction to promoting greater engagement of the learners has grown, where students bring their own ideas, experiences, and work into multiple low-stakes environments. Students consistently report an overwhelming sense of a social contract with structured peer-to-peer interactions in which they are more comfortable (“safe”) making errors in front of one another [82]. Goldschmid and Goldschmid [96] also outlined the psychosocial benefits to members of peer groups who continually alternate between “teacher” and “learner” roles, including the ability to form a more open and intimate relationship with a peer. There is a fundamental difference in audience, as Wagner [102] points out, between thinking you are providing assistance to a person who genuinely needs to your help in understanding what you know (a peer who does not know) and a professor (whom the student does not perceive as someone who lacks the knowledge).

Not surprisingly, the literature on the use of peers in writing is extensive. Rabkin and Smith [46] built their entire program around building a strong and interconnected social context for improving writing in a large first-year university setting. The clearer the sense of audience and purpose, the easier it is to reflect on what you want to say and how you want to say it. By making the decision making, and then the work, public and subject to negotiated understanding, the writer gets direct and relevant feedback. Moving up a level, this sort of classroom setting is metaphorically related to any community of scholarly discourse that relies on peer review and publication. As Shulman [103] points out, a key feature of scholarly discourse is the sense of community property, as scholars contribute, borrow, improve, and advance understanding through presentation, review, and critique of their ideas.

Two mechanisms seem to operate together in identifying the origin of the value to learners in peer presentation, review, and critique: having recent expertise and the need to explain it. In a deep study of college students’ comments, reactions, revisions and results, Herrington and Cadman [104] conclude that the “process of active reciprocal decision-making represents the primary value of peer review” (p. 184). This conclusion is aligned with Palincsar and Brown’s notion of reciprocal teaching [105, 106], wherein studying and understanding the practices of new learners who come easily to their success in a complex task is broken down into sensible instructional design. Although developed in the context of young readers, reciprocal teaching neatly overlaps with what Schwenk and Whitman [107] observed in teaching skills needed by physicians in their medical residencies. Newly minted residents were likely to be more “consciously competent” in their understanding of a medical procedure for having just learned it, relative to the senior physician, in still needing to think more explicitly through the steps, and so end up more likely to share better and more relevant information. The most meaningful questions arising from reciprocal teaching were what and where were the benefits, to learners, from teaching? Was it is from the preparation, the enactment, the discussion, or some combination of these?

The second mechanism is an aspect of teaching that is still significantly overlooked in higher education, namely explanatory knowledge. A common refrain among new teachers at all levels is one version of another of “I never knew the topic so well until I had to teach it,” a statement which reflects the questions that followed from reciprocal teaching, above. There is a body of research suggesting that this knowing/teaching relationship is profound: when you are consciously aware of the future need to teach what you are learning, you learn it better (more deeply) than you would if you are learning something for your own needs.

The potential benefits from peer-to-peer instruction were first examined with children. In 1973, Allen and Feldman [108] observed that low-achieving fifth grade students scored better when tutoring third graders, on a given topic, after only 2 weeks, than their peers who spent an equivalent amount of time studying alone. In subsequent experiments, Bargh and Schul [109] observed higher retention rates in college-level students who were told they were preparing to teach compared with their peers who did not have this condition as a part of their learning. In 1984, Benware and Deci [110] used two levels of questions (rote and conceptual understanding) to look at two groups of students under conditions similar to Bargh and Schul. After 2 weeks, the performance of the two groups on the rote learning questions was the same, but the students who had been told that they were preparing to teach (they did not) outscored their peers on the conceptual questions. Coleman *et al.* [111] used three levels of questions (recall, near, and far transfer) questions in examining a complex scientific topic in university-level biochemistry, and observed the same pattern, where students who were studying with the idea that they needed to teach what they were learning outperformed their peers in greater proportion as the level of question grew more sophisticated. Coleman calls this difference “explanatory knowledge,” and concludes that the “preparation to teach the contents of a text versus to understand it personally may influence the mental representations that are created from text” (p. 348). In 2007, Roscoe and Chi reviewed the area of “tutor learning” [112]. They conclude that, while there is strong evidence to support the idea that teaching promotes deeper learning, not every peer instructor breaks out of the information-telling mode when they actually teach, and so not everyone who participates ends up realizing the benefits.

What is missing from this “tutor learning” discussion, universally, is that all students are tutors, and this is why this topic is an interesting attribute of *Real Work*. During any traditional class, all students need to express and explain their understanding at least a few times; these events are called *examinations*, *term papers*, *projects*, or some other form of performance on which grading is based. Unless the examination does not involve high-level concepts and relies on multiple-choice testing of recall-based items, all students are responsible for teaching what they know in response to extemporaneous prompts (exam questions). The results above suggest that students who are not actively aware of their future need to teach, and do not understand that test-taking is a form of teaching, are missing an opportunity to move away from being Dora and toward Flora.

In the area of peer review and critique, Chang and Chang [113] have observed that having structures in place to support the review process is important to getting quality critiques. In a study involving students who critiqued teacher and peer-generated molecular representations for a combustion phenomenon, they observed that the review process, as an act of reflection and feedback, resulted in the student participants developing a more sophisticated understanding of the underlying science than students who did not participate in a review process.

9.2.2.1 Calibrated Peer Review

Instructional technology has provided a solution to the problem of scale when it comes to peer review and feedback. Coursera's Massive Open Online Courses (MOOCs) include an online calibrated peer review (CPR) system that involves human participation as opposed to computer-based feedback [114]. The CPR$^{\mathrm{TM}}$ system [115, 116] is an online tool that provides a great deal of flexibility for users to facilitate large-scale peer-to-peer feedback on writing assignments in their courses. Users submit written work into the system, and then calibrate their abilities to review writing on that assignment by applying an instructor's rubric to three sample essays that range from poor to excellent. Information about a reviewer's competence is logged, and students then provide anonymous reviews for some specified number of dis-identified writing assignments from their peers. An instructor may also choose to have the students then review their own work. The program has been used in many chemistry and chemical sciences classes, including lower and upper level chemistry laboratory courses [117, 118], environmental chemistry [119], biochemistry [120], and neuroscience [121].

9.2.2.2 Guided Peer Review and Revision

In the Structured Study Group program [82], we have integrated a structured peer review process into the face-to-face meeting time that the students have. When they come to the 2-h session with their work on the divergent tasks, they exchange their papers and examine a peer's work. The examination is guided by a review worksheet, on which the name of the original owner's paper and the reviewer's are entered. The worksheet is a series of questions with simple yes/no prompts [83] (Is the citation formatted correctly? Does the selected molecule meet the three criteria?). The original papers are not graded; only the yes/no questions are answered. This time is generally an open, freewheeling discussion, where the students are facing a solution to the divergent task that is different from theirs, and is yet an answer to the exact same charge. The prompt used by the upper class facilitators is also simple: as you think about whether the paper you are looking at satisfies the criteria of the assignment, think about your own work, too. On average, it takes 45 min to complete a review that does not involve marking the papers but only involves deciding whether the answer to the written prompt is "yes" or "no." During this time, however, there has been a lot of discussion and presentation of thorny issues, ranging from one-to-one questioning to whole group talk.

A second round of review is carried out the same way, except that now it only takes about 20 min to come to resolution. At this point, the original owner of the paper gets his or her paper returned, along with the review sheet of circled yes/no answers. Each student has now reviewed the work of two others, and so they are now charged with deciding, on their own work, whether there are any changes needed before they turn them in for evaluation. In studying what happens next, we evaluate an unmodified copy of the original paper, from the start of the session, and compare this with the modified post-review paper. We use a simply three-point scale (outstanding, satisfactory, unsatisfactory) to evaluate the students' work. On average, the work they bring to the start of the session can be as high as 75% unsatisfactory/25% satisfactory/0% outstanding; after the review process, when they decide whether something needs to be improved in their work, the resulting papers have moved almost completely into the satisfactory/outstanding range.

9.2.2.3 Argumentation and Evidence

Evidence and theory-based argumentation is an important form of discourse characteristic of scholarly communities. Recently, the literature around how to bring students into this discourse community as a part of their education is growing, especially in science education [122]. In chemistry, this extends to the use of appropriate representational forms while constructing an argument [123].

Students in the organic Structured Study Groups participate in a 4-week *Real Work* assignment designed to promote discussion about the characteristics of scientific knowledge. For the first week, students prepare short essays answering the question: “What is the nature of scientific knowledge and how does it compare with other forms of knowledge?” After peer review and discussion that is geared toward building consensus on the answer to this question, the students receive a copy of a published journal article that is intentionally selected for its potential controversy. For example, Mehmet (“Dr. Oz”) Oz is a coauthor on this report, which bears all the surface features of a standard research article, on the effects of healing energy on tumor cell proliferation [124]. The students are asked to read and react to this paper in the context of the prior discussion and be prepared to discuss whether or not, and why or why not, this paper satisfies their definition of scientific knowledge. Over a 2-week period, the students have time to discuss this in their individual group meetings. Finally, all the students participating in the program are brought together for a 1-h plenary session that features two guest faculty members as discussion facilitators (usually one from the bio-related sciences and one from the humanities or social sciences).

9.2.3
Balance Teamwork and Individual Work

9.2.3.1 Team-Based Learning: Face-to-Face Teams

Team-based learning [125] is an area that is distinct from group learning [126], although it relies on it. Varma-Nelson and Coppola have reviewed the use of teams in chemistry education [83], and proposed a model for team learning as a second-generation instructional strategy, in that it intentionally integrates a collection of existing pedagogical practices and theories: cooperative and collaborative group learning [127], reciprocal teaching [105], Vygotsky’s learning theory [128, 129], and studio instruction [130]. Ideally, students are tasked with something that is complex enough to require its work to be divided up into sub-tasks and brought back together.

The following is an example of a convergent problem from the PLTL group [131]. Conceptually, the problem is complex enough for introductory students that they tend to not be able to balance all the parts, that is, to suspend judgment, in a way that allows a successful solution. Instead, the aggregate experience of a team working on the problem and sharing their thinking moves them into full consideration of the issues involved.

Two isomeric compounds ***A*** *and* ***B*** *are known to each have a mono-substituted benzene ring* (C_6H_5—)*. Both have the formula* $C_6H_5C_3H_5O_2$ *and both are insoluble in water. However, when they are treated with dilute NaOH, A dissolves but B does not. Give structures for A and B consistent with this information.* ***Explain your reasoning****.*

9.2.3.2 Team-Based Learning: Virtual Teams

In a noteworthy modification of PLTL, the design and implementation of cyber-peer-led team learning (cPLTL) has been accomplished [132]. Now it is possible to create a virtual team space that maintains the features of the face-to-face meetings with the use of small document cameras, standard webcams, and networking software. The cPLTL group reports that the gains in student performance are the same in both formats. In addition, preliminary research results indicate that students in the cPLTL groups are more task-oriented than the face-to-face groups, and use more explicit explanatory language, but at the cost of less of a sense of the social benefits realized by their face-to-face counterparts [132].

9.2.3.3 Team-Based Learning: Laboratory Projects

Laboratory work is an obvious target for team-based learning and *Real Work*. In their studio General Chemistry course, Gottfried *et al.* had four-student teams, each of who selected and designed experiments for investigating the status of a local watershed that had been potentially exposed to an underground contamination [133]. The class cooperated with local and state authorities, and the student teams needed to think deeply about real-world compliance and communication as they divided their various tasks (sampling, monitoring, data recording, data storage, etc.).

9.2.3.4 Team-Based Learning: Collaborative Identification

Even in a traditional laboratory setting, some of the mundane and skill-based tasks, such as learning how to record a melting point or obtaining an infrared spectrum, can be turned into *Real Work* tasks in which individual and team-based efforts are both critical components. The following example works in settings where they might be well over a thousand students in a given course [134]. First, select 8–12 colorless organic solids that can be pulverized into identical looking powders. Add small amounts to vials, and code them all uniquely. For laboratory rooms with 22 students, create random mixtures of 30 vials, with one, two, or three vials of a given substance. At the start of the laboratory session, each student takes a vial. Their goal is as simple as it is real: by the end of the laboratory period, find out who else in the room has the same substance as you. In order to solve this problem, students now need to gather and share experimental data (e.g., melting points, solubility, thin-layer chromatographic behavior, infrared spectra) and think about shared standards (what is a solubility test and how uniform does the testing need to be), and even the student who may not have anyone in class with the same substance needs to communicate and cooperate as fully as anyone else. This blueprint can be extrapolated to any type of laboratories where comparative data can be collected on identical-looking samples (e.g., colorless liquids, solutions of acids or bases). If the coding scheme remains hidden from the instructors, which is recommended, then the solution to the problem is genuinely driven by the experimental data and the experiments that must be designed in order to reconcile ambiguities and outlying points.

9.2.3.5 Team-Based Learning: Experimental Optimization

Another *Real Work* example that takes advantage of team learning is to start with a traditional laboratory exercise and to pose a simple question for which there is no known answer but which a laboratory-sized group of students can answer. For example, in her 1000-plus student second term organic chemistry course, Shultz [135] starts with a standard textbook Wittig reaction, Fisher esterification, or aldol condensation, and poses a driving question. In the case of the Wittig reaction: using the principles of green chemistry, how could one modify this experiment? As a group, the laboratory section might decide to examine different solvents and design a series of experiments to systematically investigate different proportions of binary mixtures. Although each student is responsible for individual work, the compilation and analysis of the collective information is required in order to see trends and make generalizations. In subsequent terms, the driving question might be to start with the solvent information and decide how to optimize the yield by carrying out systematic investigations of temperature, time, concentration, and other experimental variables.

9.2.4

Students Use the Instructional Technologies

9.2.4.1 Learning by Design

Whatever technologies enhance the ability of teachers to design instruction must also enable the ability of students to convey their emergent understanding [136]. According to Coleman's ideas about explanatory knowledge in the sciences [111], as well as Kozma's work in representational competence [137, 138], arming students with multiple and varied explanatory or representational tools will promote deeper learning of the baseline subject matter as they think about and organize their understanding in anticipation of conveying it to others [139]. Exactly the same caveat about effective and ineffective choices in faculty use of presentational tools applies to students, as any technological tool "will not turn a bad presentation into a good one, and will not convert an ineffective presenter into an effective one" [140].

As a cornerstone of work in the arts, using student-generated work in order to promote learning has been adopted in science education under the "learning by design" framework, which emphasizes, as the name implies, the value of actively designing and constructing something [141]. In a study of students who generated videos in K-12 settlings, Kearney and Schuck [142] observed *Real Work* outcomes. Open-ended tasks with a high level of control over task development resulted in learners who took a high degree of ownership and autonomy, with a strong sense of audience (peer instruction). The tasks, which ranged in context from language classes to topics in the sciences, were complex enough to elicit high levels of meaningful team learning. Comparable results were observed with university undergraduates in the case of a virtual solar system project that resulted from a highly peer-based learning design [143].

9.2.4.2 **Electronic Homework System: In the Classroom**

Moore has merged the use of a commercial homework system for organic chemistry with a modified classroom design [144]. Students in his organic chemistry class learn to operate within a software platform that allows drawing organic molecular structures, mechanisms, and energy diagrams. Moore directs in-class activities, all of which are mediated by students generating drawings in response to these prompts. With the level of comfort for using this system that is developed this way, the students then take their examinations in the same platform, which also handles multiple chances and the subsequent grading.

9.2.4.3 **Student-Generated Videos**

In collaboration with the campus's writing center, Shultz's (G.V. Shultz, private communication) students, in General Chemistry Structured Study Groups, generate video-based lessons for introductory chemistry topics after having identified existing video lessons that they critique as less effective than they could be. Over a term-long period, these students use principles of rhetorical analysis to craft the framework for their lessons: introduction, sources of authority, ethos, logos, pathos, metaphor, coherence, and conclusion. They are required to integrate and explain the use of at least three of these principles into their video. Students almost always include “pathos” (an emotional appeal) in their video and recognize it as an essential element that is often missing in their course lectures or videos they find online. Also, pathos is an element that is almost always present in the videos that they rated highly.

9.2.4.4 **Student-Generated Animations**

High school students who generate visual representations for chemical phenomena are more successful in understanding the underlying concepts than their counterparts who select between pre-existing representations, depending on whether the selections are simple or complex, suggesting that the combination of student-generated work with identification may be a powerful combination [145]. Student-generated dynamic representations (movies) for these arguably dynamic phenomena are rarer. University-level preservice primary school teachers learned to create “Slowmation” (low frame rate) animations [146], which contributed positively to their learning and helped clear up errors in their thinking. Organic chemistry students have constructed animated gifs of complex mechanisms for

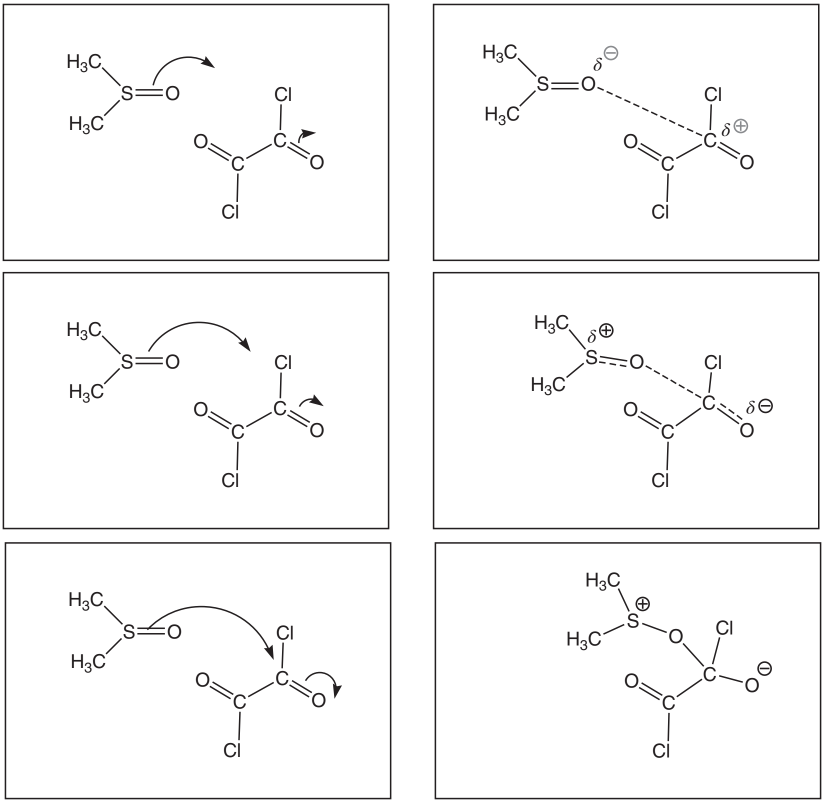
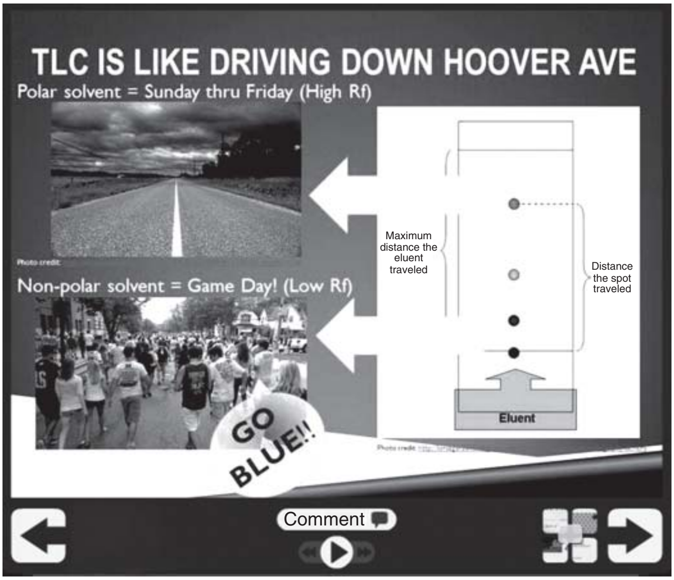


Figure 9.4 Six selected slides (out of 50) from a student-generated animated gif for the Swern oxidation mechanism.

literature-based reactions [86] (Figure 9.4). They report that the fine grain size required for creating a hundred or so frames of these easily constructed animations causes them to think more deeply about, and in some cases self-correct, the impression they got from the traditional, static, single-panel, curved-arrow representation. ChemSense [147] and Chemation [148, 149] are two software environments that were built, based on the earlier work with animated gifs, to provide greater scaffolding for creating animations and linking these together with molecular properties.

9.2.4.5 **Student-Generated Video Blogs**

Lawrie and Bartle [150] asked students to create 2–3-min video blogs (vlogs) that targeted explanations for structure–property relationships, and found a positive correlation between the level of sophistication of the representations, the depth of the explanation, and the standard achievement level of the students who created the vlog. Shultz [151] has integrated a video blog platform (VoiceThread) into the laboratory experience of a large-scale organic chemistry course, with a particular emphasis on students making self-explanations [97, 112] for their process of



TLC IS LIKE DRIVING DOWN HOOVER AVE

Polar solvent = Sunday thru Friday (High Rf)

Non-polar solvent = Game Day! (Low Rf)

Figure 9.5 Still frame extracted from a video blog describing an analogy for thin-layer chromatography. (Original presented in Ref. [151].)

analyzing experimental data when carrying out structural identification. Her students have reported that it was helpful to see how others had perceived the same content and that explaining helped them to better understand the material being presented. A frame from one of Shultz's students' explanations, which used an analogy for thin-layer chromatography, is shown in Figure 9.5.

9.2.4.6 Wikipedia Editing

Student authorship becomes more meaningful when the purpose becomes more real [46]. Moy *et al.* integrated learning to edit and author Wikipedia articles into a graduate-level polymer chemistry course [152], and others in this department followed suit at both the graduate and undergraduate level. Undergraduate students improved articles that involved standard named reactions (e.g., Jones Oxidation, Appel Reaction, Ritter Reaction).[1]

9.2.4.7 Wiki Environment

Moore asked students to master a collection of six molecular representational tools and then to construct and peer-review, in a Wiki environment, details of the mechanisms of action of a series of biologically active molecules [153].

9.2.4.8 Student-Generated Metaphors

Inherently, technologies are things that enable other things. In this attribute of *Real Work*, we are gathering those enabling strategies that an instructor might

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[1] Wikipedia.

use to teach effectively, and looking at how encouraging students to use those selfsame technologies, according to a larger precept of reciprocal teaching, provides an important lens through which student understanding can be viewed. These technologies are not at all limited to computer-based strategies. And so, to the degree that an instructor might use metaphor in order to activate the prior knowledge of students in order to build a bridge to a new concept, instructors who ask students to provide metaphors is, in effect, sharing and encouraging an effective teaching strategy. Lancor [154] reported an analysis of metaphors generated by students from multiple disciplines in order to examine their understanding of energy concepts.

Visual metaphors can be useful guideposts for navigating complex ideas [155]. In chemistry, where visualization of unobservable species is central to the science, there is substantial overlap between a scientific models and metaphors [156]. In the “HTML Project” (see Section 9.2.6.3), students use visual metaphors to contextualize the instructional materials that they are creating. In Figure 9.6, a synthetic sequence in organic chemistry is displayed as a road trip across the United States, with different features of the work (e.g., the animation of a mechanism) showing up under links for the analogical site in a city (e.g., the site of a theater).

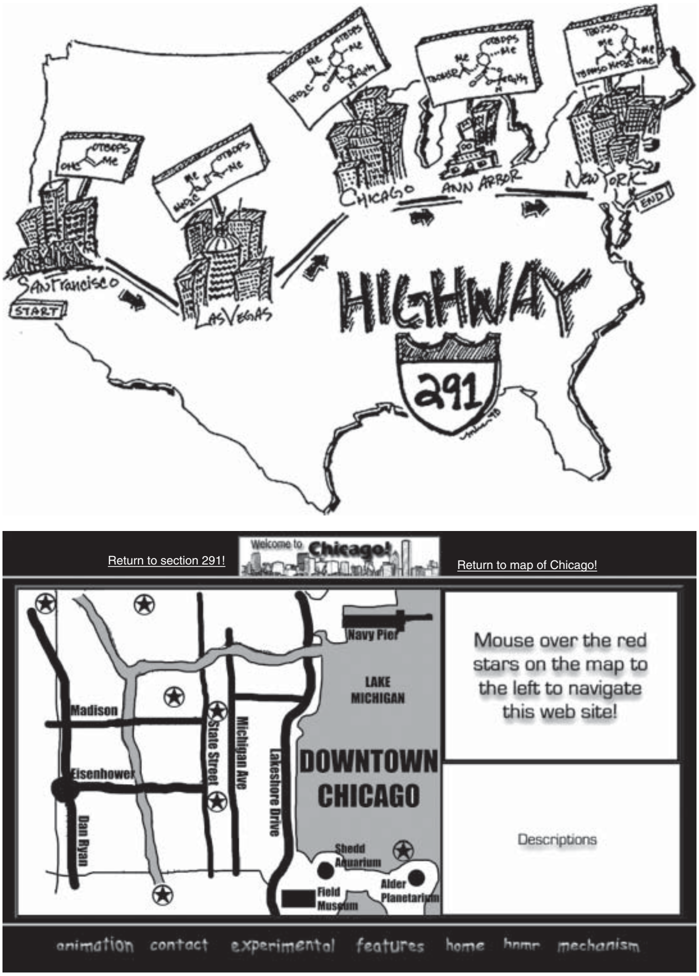
9.2.5
Use Authentic Texts and Evidence

Reading and making meaning from text is a core skill in learning, and something that Bereiter supposes that Flora does better than Dora, because she can transfer what she has learned from one situation to another. Understanding how successful learners do this, and turning this into ways to help others, has been of longstanding interest to educational psychologists. In a 1996 review of this area, Mayer [157] concludes “the most effective method for teaching students how to make sense out of expository text is for students to participate in selecting, organizing, and integrating information within the context of authentic academic tasks” (p. 357).

Tasks involving learners using the primary research literature have been unusual in undergraduate science education, particularly at the introductory level [82, 158, 159]. In the laboratory, authentic evidence can arise from research activities [160, 161] that are observed to develop a deeper understanding about the nature of science, or might arise from students being provided with empirically derived data upon which new questions are asked [162]. Perhaps because organic chemistry is the first discipline-centered chemistry class students take [11], using the primary literature as a source for assignments has become increasingly represented in chemistry education as access to and availability of electronic resources has grown [163].

9.2.5.1 **Literature Summaries**

Students in Gallagher and Adams’s [164] Honors organic chemistry class used journal articles to connect their classroom learning to contemporary scientific



Mouse over the red stars on the map to the left to navigate this web site!

Figure 9.6 Navigating “The HTML Project.” The students in Section 291 used the visual metaphor of a road trip across the United States to contextualize their five-step synthetic sequence.

writing, and through a multi-week assignment, they needed to collaborate with both peers and professors in order to make meaning from these articles. A similar approach involving first-year students and two brief summary assignments of accessible literature sources was reported by Forest and Rayne [165] to lower the intimidation barrier for subsequent use of primary sources, particularly searching for what constitutes relevant subject matter.

9.2.5.2 **Literature Seminars**

Almeida and Liotta [166] carried out a literature-based seminar for students taking both organic chemistry and cell biology in an effort to better integrate the learning in these two related classes. After one round of reading and discussion led by a faculty instructor, teams of students then select and lead the discussion of publications in which the fundamental subject matter from both classes is relevant. Students report that this work reduced their anxiety and hesitation about research, which likely contributed to the high fraction of the seminar participants who actively sought out and obtained undergraduate research positions.

9.2.5.3 Public Science Sources

Critical reading of public science sources, such as newspapers or the Internet, is another use of authentic sources. In a detailed study of using newspaper sources with high school chemistry students, Oliveras [167] found that topics such as identifying the purpose or intent of the author was a major challenge for students, as was understanding what constituted evidence and how it was used to warrant an argument. Glaser's [168] taxonomy of "Chemistry is in the News" includes the combination of reading relevant news sources, connecting these with course content, and conducting reviews of writing that range from instructor-led to peer-led, and including, at the highest level, international participants.

9.2.5.4 Generating Questions

Generating questions is an important skill of critical reading [169–171]. Deciding what constitutes a good question is an activity that can be facilitated by peer review. Structured Study Group participants [82] read a research paper written by one of the faculty members in their home department with the goal of creating questions for the author. They find that generating questions is easy, but some questions ("What does DMSO stand for?") are better answered own your own than taking up someone's time. In a 3-week assignment, these students generate questions that would be worthwhile to ask the author of the paper, discuss what constitutes a good question, and share and peer-review their questions. Finally, in a 1-h plenary session, the group meets with the author, confident with their peer-reviewed questions in hand, who carries out a dialog spurred by those questions [172]. Invariably, in addition to the subject matter of the article, the questions include many topics for which one cannot simply look up answers: how research is funded, what motivated the research, why did you get into science, what practical applications are there, do you have children (asked nearly exclusively of women), what about environmental concerns, what if the research done with an industrial partnership is contributing to activities with which the researcher has moral objections?

9.2.5.5 Course-Based Undergraduate Research Experiences (CURE)

Using authentic texts in a laboratory in order to propose, design, and carry out actual research is a growing area of activity. Access to instrumentation combined with the ability to get meaningful information from small-scale preparations has contributed to this increase. In an early example of this in organic chemistry [84], students in a large laboratory course were given a journal article in which a zinc-mediated allylation was carried out on a reported set of 10 or so aldehyde substrates. During the first laboratory period, students repeat one of the reported examples (a convergent task), to test their skills against the standards reported in the paper. During the subsequent two laboratory periods, the students (i) apply their learned skills to a substrate or reagent that was not reported in the paper and (ii) examine whether their result (positive or negative) is reproducible by a peer. The Center for Authentic Science Practice in Education (CASPiE, [173]) has developed research-based undergraduate curriculum materials, as well as guidelines for how individuals can develop research-based projects. At the end of a 2-year study in biology education, a group has reviewed this type of work and proposed that the following criteria might define course-based undergraduate research experiences (CURE): use of scientific practices, discovery, broadly relevant or important work, collaboration, and iteration [174].

9.2.5.6 **Interdisciplinary Research-Based Projects**

Using interdisciplinary research as a design for *Real Work* is a compelling target, given the increasing need for graduates to communicate (read, write, collaborate) across traditional disciplinary lines. Chemists and biologists at Seattle University [175] have created an environmental research project on pyrethroid pesticides that is carried out across three laboratory classes. Approximately 100 students, who are enrolled in Ecology Laboratory, Instrumental Analysis Laboratory, or Organic Laboratory III, begin the term in a plenary session to view and discussion a video documentary on water pollution. Students in the Ecology class collect water samples and carry out a series of abiotic and biotic analyses. The samples are passed to the organic chemistry students, who carry out reverse-phase solid-phase extraction. The resulting organic materials are then passed to the analytic chemistry students for LC-MS/MS (liquid chromatography/tandem mass spectrometry) analysis.

Kosinski-Collins and Pontrello [176] report a chemistry-to-biology hand-off where over 80% of the students are co-enrolled in the two involved laboratory courses. Students in the organic course synthesize polypeptides that are mutants with respect to a known anti-aggregation factor that is a potential drug candidate for Huntington's Disease. About 10 new inhibitors are synthesized each time the course is offered. The molecules are then tested by the biology students in Drosophila, which express the polymer target as potential inhibitors, via fluorescence spectroscopy and lifespan analysis.

The Distributed Drug Discovery (D^3) project [177, 178] is an international collaboration, and argues "that if simple, inexpensive equipment and procedures are developed for research in each of the core drug-discovery stages, computational chemistry, synthetic chemistry, and biochemical screening, this large research challenge [drug discovery for diseases in the developing world] can be divided into manageable smaller units and carried out, in parallel, at multiple academic and industrial sites" (p. 3). To date, a project involving undergraduate students in four countries has demonstrated proof of concept for the synthetic chemistry piece, generating a catalog of over 24 000 acylated unnatural amino acids.

9.2.6
As Important to the Class as the Teacher's Work

9.2.6.1 Student-Generated Instructional Materials

The attributes of *Real Work* include using authentic sources (text and data), using the tools that professionals also use, collaboration and peer review to bring intentional reflection into the generation and refinement of artifacts, and encouraging creativity through the balance of convergent and divergent tasks. In the previous section, a high sense of purpose accompanies *Real Work* tasks that target the creation of new knowledge when students are carrying out research. Our last attribute is a highly underdeveloped area: student-generated instructional materials. Another way to instill immediate purpose for student work is to design tasks that return to the classroom, and for which all members of the class are responsible for, in the deepest sense; they are responsible for generating instructional materials, and they are responsible to these, collectively, as a part of their learning in the class. Lee and McLoughlin have reviewed the emergent area of using "learner-generated content" in instruction [179], and Perez-Mateo *et al.* have proposed an extensive set of quality criteria for those assessing this kind of work [180].

Computer Science faculty have been particularly active in this area, which they call "contributing student pedagogy" [181, 182]. There are a variety of proposals on why this pedagogy is so effective, including introducing high value (purpose) in a peer-to-peer context [183], requiring formative peer review [184], developing intrinsic motivation [185], building upon social constructivism and community-based learning [186], and facilitating constructive evaluation [187].

9.2.6.2 Wiki Textbooks

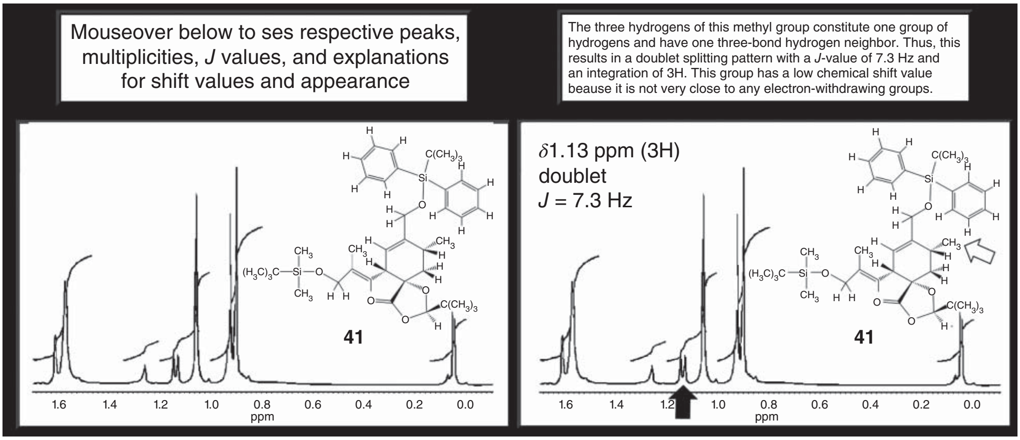
New technologies have enabled authorship for individuals, and can also enable students to author their own textbooks, or supplementary text materials [188, 189]. Wheeler *et al.* [190] posit the growth of "user-created knowledge" through Wiki technologies as an "architecture of participation" (p. 989). Kidd *et al.* [191] have reviewed the brief history of Wiki textbooks, and the corresponding challenges [192], in the context of preservice teacher education, with benefits accrued to future teachers that derive from their thinking about teaching (writing a text) in such a concrete way. The same group has also provided perspective on a peer-review system that is appropriate to a term-long project with multiple contributors, such as a Wiki textbook [193]. Subject areas such as reading and second language acquisition have benefitted from using books derived from student-generated instructional materials [179]. In chemistry, Pazicni *et al.* [194] have described how student-generated materials were used to supplement the traditional text in an introductory physical chemistry class through a term-long, on-going Wiki project. Bruce *et al.* found that a student-generated E-glossary was particularly useful for nontraditional students and non-native English speakers because of the direct relevance to the course and its one-point access [195].

9.2.6.3 **Print and Web-Based Textbooks**

Since 1994, in the second term of the organic chemistry Structured Study Group program [82], students carry out a project that integrates all of the *Real Work* attributes. Over the duration of the 13-week term, a class of about 125, in five teams of 25 students, each led by an experienced upper-level undergraduate facilitator, carries out "The HTML Project" [86]. As a part of their weekly group work, each 25-student team is divided into subgroups with three to four members. Each of the five large teams is responsible for learning the chemistry in a specific synthetic organic chemistry reaction sequence located in a journal article selected by the instructor. Each team has a different article and a different sequence for which they are responsible. The chemistry in these sequences is more or less relevant to a second-term course in organic chemistry, and new papers are used every year. In each team, the reaction sequence is divided up between the subgroups. In other words, subgroup 1 might have responsibility for learning the transformation of compound **13** to compound **14** (in some sequence), subgroup 2 is then responsible for the transformation of **14**–**15**, and so on (Figure 9.6).

Every week, there is work that needs to be done on pieces of the project, which are (i) to research what is known about the mechanism of the reaction, (ii) to display the mechanism in its traditional one-panel, curved-arrow format and to construct an animated gif (e.g., Figure 9.4) using the freeware program GIFBuilder [196], (iii) to provide a detailed interpretation of the relevant spectral data and to create both text and graphical correlations (e.g., Figure 9.7), (iv) to answer some leading questions on the chemistry, and (v) to annotate the experimental procedure. All of the intermediate work, for example, the storyboard for the animated mechanism, is peer-reviewed, critiqued, and revised, accordingly. A few weeks before the end of the term, the work of individual subgroups is compiled, and the work of all five teams is gathered together, resulting in a 200–250 page printed text and its accompanying Web site, where members of this class of 125 students have all contributed to the analysis and interpretation of (i.e., "unpacked") the chemistry behind these syntheses and presented them as instructional materials for their peers.

In addition to its obvious purpose in having these students dig into the detail of these journal articles for deep understanding, the HTML serves one last relevant purpose as instructional material: the final examination in this course is based on questions posed by the instructor about the work in the student-generated text, in the context of their second-term organic chemistry course. Moreover, the students are told that the questions are only based on whatever lingering errors might exist in their work. The examination is open-book, that is, they need to bring the book they wrote, which can be annotated to whatever degree they want. The instructor stands aside and does not engage in the resulting discussion about possible errors, as the students have the name of the people who wrote every word and drew every structure as classmates. From an instructor's perspective, this examination is a



Mouseover below to ses respective peaks, multiplicities, *J* values, and explanations for shift values and appearance

The three hydrogens of this methyl group constitute one group of hydrogens and have one three-bond hydrogen neighbor. Thus, this results in a doublet splitting pattern with a *J*-value of 7.3 Hz and an integration of 3H. This group has a low chemical shift value beause it is not very close to any electron-withdrawing groups.

δ1.13 ppm (3H)
doublet
J = 7.3 Hz

(a) (b)

Figure 9.7 (a,b) A typical mouse-over spectral correlation and analysis generated by students as instructional material for their peers (arrows have been substituted for the usual technique, where the relevant portion of the spectrum and the group of atoms in the structure are indicated in color). The cursor can be placed over the signal or over a set of atoms, and the corresponding information and explanation are then provided to the user.

critical culmination to the project, giving the work the highest possible value in the context of a course, and teaching an overarching lesson about scientific skepticism: when you open a resource and begin to read, you should always be asking yourself a few questions: do I believe this? Does the evidence warrant the claim? A typical examination question might be “On page 65 of your book, the authors showed dichloromethane as a proton source for the second step of the transformation. Why is that incorrect, and provide the more reasonable mechanism for this reaction.”

One of the recurring assignments in the organic chemistry Structured Study Group program [82] is for students to transform an example from the primary literature into an appropriate examination question. The organic chemistry program at the University of Michigan uses literature-based examination questions in both of its introductory courses [84, 197, 198], and so this task is highly relevant (e.g., Figures 9.8 and 9.9). Students are divided up among various organic chemistry journals with different publication years, and given the divergent task of locating an appropriate reaction (e.g., a bimolecular nucleophilic substitution reaction, drawing resonance contributors, an electrophilic addition reaction) and transforming it into an examination problem, complete with a brief contextualizing statement, a citation, and an answer key. During the subsequent weekly session, the question and all of its associated parts are peer-reviewed, and the author makes whatever corrections might be needed on the spot. The reviewed questions are then exchanged once again, without the answer key, and the students solve the peer-generated problem as practice.

9.2.6.4 **Electronic Homework Systems**

Fergus and Kirton [199] report training 237 students on the PeerWise platform [200], which enables students to generate multiple-choice problems that can be accessed by their peers. Here, the undergraduate chemistry students were required to generate two problems, answer five, comment on three, and provide

When treated with a Bronsted acid catalyst, compound **P** was transformed into compound **Q** (isocumene) through a mechanism involving two reactive intermediates (*JACS* **1981**, *103*, 82). Provide the structure of the first intermediate (resulting from protonation), the mechanism for its transformation to the second intermediate, the structure of the second intermediate (which is then deprotonated to give compound **Q**). The protonation and deprotonation mechanisms do not need to be shown.

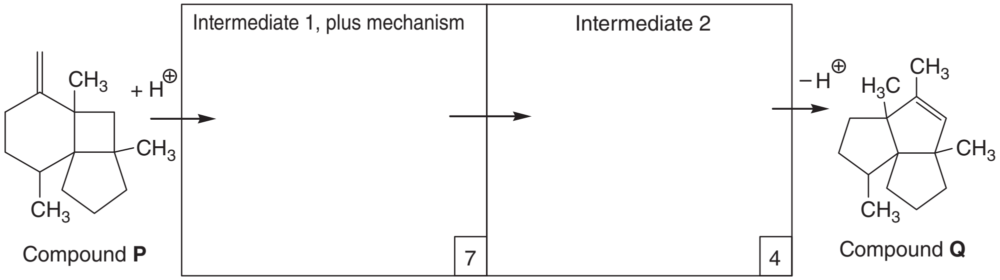


Figure 9.8 Typical example of a faculty-generated, literature-based examination problem.

Squaric acid (Compound **D**) has been used to treat warts in children who have a skin infection caused by the human papillomavirus (*J Am Acad Dermatol* **2000**, *42*, 803). The doubly deprotonated form of squaric acid (Compound **E**) is a di-anion that has a set of 3 other significant resonance contributors that (i) have all closed shell atoms, (ii) maintain charges of –1/0/+1 on the atoms, and (iii) keep the negative charges located on the oxygen atoms.

Draw these three other resonance contributors. Be sure to show all electron pairs and formal charges.

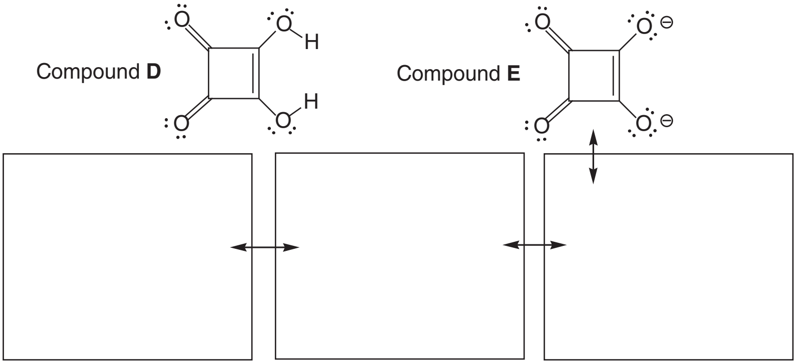


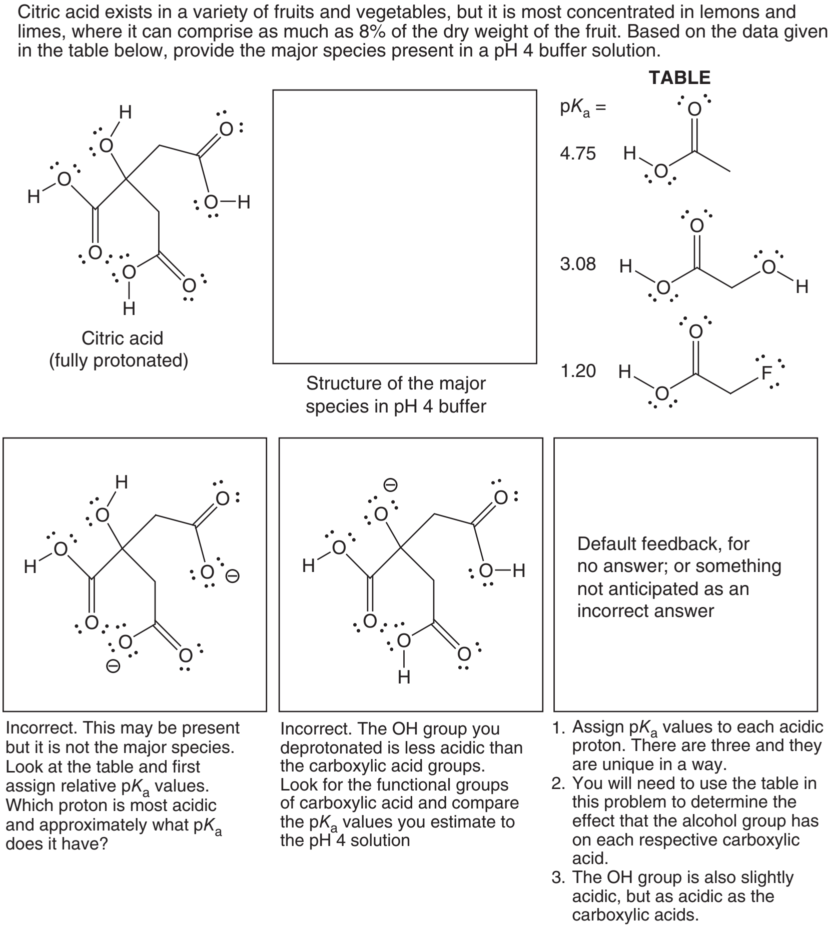
Figure 9.9 Typical example of a student-generated, literature-based examination problem.

ratings. Only three students did not produce any questions, and over 75% of the students answered more than the required number. Burkhalter and Wilson [201], teaching in online chemistry and biology courses, have used student-generated multiple-choice questions as an assignment which then increases the number and diversity of the problems in their test banks.

During the Fall 2013 semester, Coppola and McNeil (Unpublished results) trained 142 first-term first-year undergraduate students in the organic chemistry Structured Study Group program on how to be authors for the Sapling Learning e-homework system [202]. At the end of the term, out of a total of 167 completed problems, which were all targeted at skill-building exercises for learning the curved-arrow representational system, there were 61 that were rejected for content problems severe enough to not warrant revision, 46 that needed major revision, 33 that needed minor revision, and 27 that were publication quality (Figure 9.10). The major issue was that, once an undetected conceptual error entered the system, it was propagated through the numerous incorrect answers to the point where revision was simply too laborious. The solution: a more robust review process during the development stage. During the Spring 2014 term, 31 of the already-trained students generated 637 problems in 10 different skill areas, and nearly all of them were publication-ready without the need for revision. These student-generated instructional materials will be available to all students in subsequent offerings of this class.

9.2.6.5 **Podcasts**

Student-generated podcasts, including visual enhancement, are another growing area of student-generated instructional materials [203]. Even in creating brief



Citric acid exists in a variety of fruits and vegetables, but it is most concentrated in lemons and limes, where it can comprise as much as 8% of the dry weight of the fruit. Based on the data given in the table below, provide the major species present in a pH 4 buffer solution.

Default feedback, for no answer; or something not anticipated as an incorrect answer

Incorrect. This may be present but it is not the major species. Look at the table and first assign relative pK_a values. Which proton is most acidic and approximately what pK_a does it have?

Incorrect. The OH group you deprotonated is less acidic than the carboxylic acid groups. Look for the functional groups of carboxylic acid and compare the pK_a values you estimate to the pH 4 solution

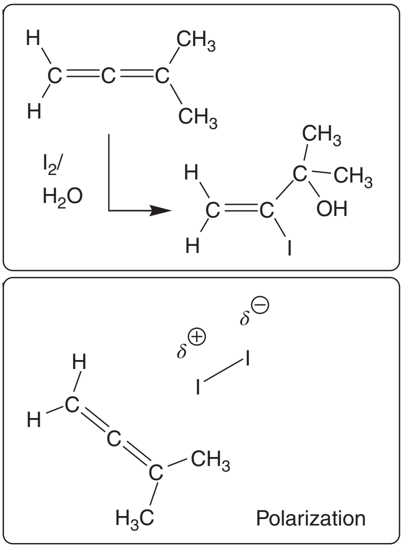
1. Assign pK_a values to each acidic proton. There are three and they are unique in a way.
2. You will need to use the table in this problem to determine the effect that the alcohol group has on each respective carboxylic acid.
3. The OH group is also slightly acidic, but as acidic as the carboxylic acids.

Figure 9.10 A student-generated problem for the Sapling Learning environment, including two anticipated incorrect answers, feedback for them, and the default feedback.

segments, students need to consider a broad array of issues in teaching and learning as they prepare their products for broadcast to their peers: scriptwriting and editing, presentation, audio recording and editing, publishing, and distribution [204]. Between 2006 and 2012, teams of two to three students in the first-term Structured Study Group program [82] selected a test problem from the annual collection of old examinations, which is one of the learning resources in the organic chemistry courses. Although these problems intentionally do not have a readily available answer key as a part of the strategy for getting students to work together and share their ideas, podcasts provided a way to create a new resource. Thus, over a 4-week period, each student team was tasked with creating a 3–5-min visually enhanced podcast that was aimed at providing a step-by-step tutoring lesson on how one would solve the problem. Over the 4-week period, the team would bring to the session their draft script, their storyboard, their draft podcast, and the revised podcast, and the rest of the group would provide feedback. Each student participated in the construction of one podcast during the term, thus only a subset of students generated these podcasts from problems relevant to each of the exams. The block of problems, and the podcasts generated by this group of about 160 students, then became available to the class as a whole during subsequent years. Over a 6-year period, almost 400 of these visually enhanced problems were created. About 15% of the students in the large 1500-student class report regularly using this resource and perceive them to be useful. The students have not shied away from creative contexts for building their explanations, with scripts that might be done in the form of a newscast (Figure 9.11) or a rap performance (Figure 9.12).

9.2.6.6 **Classroom: Active-Learning Assignments**

Providing structure and guidance for students is an important feature in the design of this *Real Work* attribute. By breaking down the task into manageable pieces and providing ample opportunity for feedback, the quality of the work produced can be acceptable for release to other students. In a two-term Computer Science course, Gehringer and Miller [205] assigned students to create curricular activities which then constituted part of the course syllabus. Starting with 30–40 min of class time immediately following a lesson, their students drafted an active-learning exercise based on the course material. Over the next week, the activities were (i) posted on a Wiki page, (ii) reviewed and commented upon by peers, (iii) revised, and (iv) reviewed a second time before incorporation into the course.



"Hi, and welcome to CHEM BC News. I am London van der Waals and this is my co-anchor, Jenny Neutron."

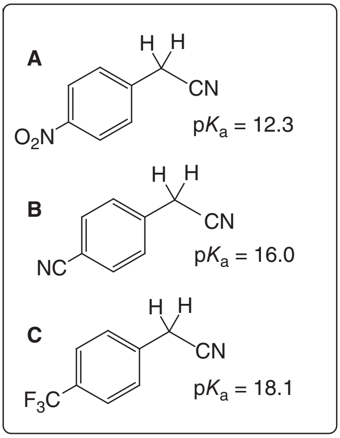
"Thank you, London. Today we are going to explain the mechanism for this electrophilic addition reaction found on page 161 of the coursepack." ...

"As the iodine molecule approaches the double bond it become polarized due to electron–electron repsulsion between the electrons of the alkene and the electrons of the iodine molecule."

"Really?"

"Yes, Jenny. One iodine atom actually becomes more positive while the other becomes more negative. The partially positive iodine atom is now electrophilic..."

Figure 9.11 A student-generated, visually enhanced podcast explaining the mechanism of an electrophilic addition reaction (excerpt from script).



The pK_a values in DMSO,
For Molecules ABC, given below,
This question's testing you to see if you know,

The Reasons for the pK_a's that they show.

So look at **A**, right? thinking about the NO_2 group you might say.

So, nitro why you make the pK_a low, it's cuz you pull electrons across the aromatic ring, yo

I'm like, oh, induction, I see

Are there any other reasons for the reactivity?

I'm looking at this think wondering what else you got...

Figure 9.12 A student-generated, visually enhanced podcast explaining the difference in pK_a values for a series of compounds (excerpt from script).

9.2.6.7 Laboratory: Safety Teams

Turning over some of the actual face-to-face instruction in a course is another way to think about student-generated instructional materials. Alaimo *et al.* [206] created 2–3 student safety teams from each general and organic chemistry laboratory section. Each team was responsible for (i) preparing a pre-lab discussion on some prescribed safety topic(s), including handouts, (ii) monitoring the laboratory during their assigned period for safety issues, and (iii) carrying out a post-lab inspection. Students who took responsibility for this work outperformed a group of their peers, in whose course these safety teams were not formed, on a set of basic safety questions.

9.3
Learning from Real Work

Integrating *Real Work* into instructional design requires greater organization and effort than standard didactic teaching and testing methods. The attributes of *Real Work* described in these examples all attempt to elevate Dora's penchant for schoolwork [1] ("homework" that emphasizes memory, recall, and algorithmic heuristics) to Flora's real-life approach ("real work" that builds on prior knowledge, application, and evaluation). Unfortunately, it is far easier for research to evaluate Dora's skills than Flora's, and so they both do well on their Algebra I tests and on other evaluation instruments that focus solely on providing answers to problems. Compelling evidence for Flora's deep understanding, the transformation in her learning because of her instructional environment, is contextualized in her ability to have learned Algebra I in a way that allows her to succeed in Algebra II.

In a meta-analysis of 40 years worth of innovation and reform in higher education, Slavich and Zimbardo [207] have proposed a compelling framework for the basic principles that derive from transformational teaching and learning. In order for Flora to have been considered educated, she should exhibit evidence three things (p. 582): (i) acquisition and mastery of key course concepts, (ii) enhanced strategies and skills for learning and discovery, and (iii) positive learning-related attitudes, values, and beliefs. The authors propose educational psychological gains in motivation and self-efficacy as exemplars for their interesting third category. But this category could easily be expanded, in discipline-centered science education [208], as the "ways of thinking, feeling, and behaving," that is, scientific dispositions: those things that accompany learning the subject matter [209] but are not easily quantified and do not appear on the syllabus, such as improving one's evidence-based skepticism.

9.3.1

Evidence of Creativity through the Production of Divergent Explanations

Trivic *et al.* [210] studied the explanations given by two groups of students learning stoichiometry, one of whom experienced a highly convergent instructional design (demonstrations and calculations), while the other group was participating in experimental and textbook work that included the chance to generate, share, and review stoichiometry problems with one another. The second group not only showed a larger gain on standard pre/post comparisons, but they also generated a more diverse, multirepresentational set of replies, integrating more conceptual categories, such as solution chemistry, the periodic table, and a historical approach to chemistry.

9.3.2

Peer Review and Critique Reveal Conceptual Weaknesses

The CPR^{TM} platform [211] has been an enabling technology because it allows the aggregation of information about student writing on a large scale. In using CPR, which is a Web-based tool, students deposit written assignments. They then read examples of written assignments provided by the instructor, which range in quality, and use rubrics to train themselves (calibrate) against these examples. Finally, they are provided access to other student work to read, review, and leave feedback, guided by the rubrics and by their training. Pelaez [212] compared two physiology classes, one of which used problem-based writing with peer review in place of didactic lectures, and observed a sharp difference on exam performances. She was also able to use the original writing, and its reviews, as evidence from which to generalize problem areas in student learning which, in turn, allowed subsequent classroom discussions to be more targeted at specifically those areas. In addition to recurring difficulties with specific topics (e.g., vesicles) and higher level organizational concepts (relationship between intra and intercellular features), the student writing also revealed conceptual difficulties with broader ideas about scientific thinking (cause and effect; overgeneralization of principles).

The majority of users of this online peer review system report high levels of satisfaction with student engagement and the ability to provide feedback to students in both classroom and laboratory sessions [116, 121]. Margerum *et al.* used CPR to integrate environment chemistry subject matter into a laboratory course, and noted (i) the ease with which this allowed them to bring these aligned topics into the course with minimal effort and (ii) that working through a written description of the laboratory work improved the quantitative analysis of the experimental data. Berry and Fawkes also report an increase in the quality of student writing, by focusing sequential assignments on different portions of the laboratory report, with minimal added effort [117].

Using a longitudinal series of assignments, Walvoord *et al.* [213] carried out a careful study on whether using CPR^{TM} assignments improved the general quality of student writing and their ability to convey scientific knowledge. Using comparisons between student and faculty scores, the researchers looked at the overall quality of the student reviews. Two external writing experts reviewed the student work for its technical communication skill. Based on this study, the overall quality of the writing did not improve over the term, and neither did the technical communication skills, which is different from what Gunersel *et al.* observed using a repeated measures analysis in an upper level biology course [214]. The most important conclusion here [215] is that the use of any instructional methodology is not one-size-fits-all, and is highly conditional on the setting, the specific assignments, the degree of support, the level of student experience in the subject, and the willingness of the faculty member to invest appropriate time aligning the pieces into a coherent learning environment.

9.3.3
Team Learning Produces Consistent Gains in Student Achievement

The most typical data collected in studies on team learning are examination performance, overall grade distributions, and retention. The results across many studies, including longitudinal ones, are robust: integrating structured, facilitated, peer-to-peer time into classes improves all these factors [216]. In general, the observed gains do not favor gender, race, or ethnicity. The degree to which gains result from deep, conceptual understanding versus targeted, time-on-task preparation is still an open question; that is, %Flora versus %Dora [78]. Some of the most impressive results reported suffer from a combination of self-selection bias and comparison groups with no equivalent time on task, so it is difficult to make confident claims on the mechanism of these observed changes [217].

Quitadamo *et al.* [218] used existing survey instruments to try and gauge whether critical thinking skills were being affected, but the results were modest and not triangulated with other data. Deeper insights into what is happening in these teams, using multiple methods including discourse analysis, have been obtained [219]. The results are consistent with the conclusion above: there are no bulletproof designs [220]. The groups that were studied ranged from productive and interactive to didactic and answer-telling, depending on the teacher – student dynamic [112]. Differences in the face-to-face and cyber settings have also been studied using both quantitative methods and discourse analysis, and compelling differences based on the degree of intellective commitment and social engagement was observed (P. Varma-Nelson, private communication January 17, 2014).

Facilitators for peer-led groups might be predicted to experience the "tutor learning" effect [112]. Gafney and Varma-Nelson studied in detail almost 120 peer leaders at multiple institutions [221]. They affirm that these students, who are not tutors but rather discussion leaders, also have the knowledge of the subject matter reinforced, both in breadth and in depth, and that they realized personal benefits such as increased confidence, perseverance, public speaking, and organizational skills.

In the Structured Study Group program [82, 83], through the peer review and critique process learners start with student-generated work at the start of their sessions and invariably end up needing to reject and correct parts of their assignments which they thought were correct. In order to see whether we could observe this as a transferable skill, we looked the ability of students in this program to work their way out of a discrepant, counterintuitive observation after they have made an incorrect prediction about a familiar phenomenon, and compared their performance with high-achieving students who were all in the same course but who did not elect the Structured Study Group option [197]. While none of the students in either of the groups made the correct prediction, thus creating a level playing field for the study, 80% of the first-year university students who had spent 2 h per week engaging in this structured review process, including rejecting and correcting work they thought was originally acceptable, resolved the discrepant observation in a way that was similar to a comparison group of first- and second-year graduate students. In contrast, only 10% of high-scoring students who did not participate in this group work demonstrated skills that were comparable to the graduate students.

9.3.4
Students Use Instructional Technologies

Lazzari [222] looked at multiple dimensions of student learning for a group of students who generated, as well as used, short podcast lessons, relative to another group of students who only used them but did not generate them. Using both quantitative and qualitative methods, the students who generated podcasts placed this activity as a significant contributor to exam scores, course satisfaction, and as a dominant talking point during interviews. He concludes that it is likely "that podcasting design, recording, and editing spurred the development of reflective learning skills, stimulated students to go deep into the questions they had to face, and fostered positive collaborative behaviors, promoting growth of students' collaborative learning skills" (p. 32).

9.3.5
Using Authentic Materials Result in Disciplinary Identification and Socialization

Russell and Weaver [160] have compared the effects of traditional, inquiry-based, and research-based laboratories in chemistry, and the results are consistent with the prediction that the more authentic context results in greater gains in the more authentic conceptions about science and scientific practices. Their study covers large and small settings over a range of institutional types, and involved a combination of surveys and randomly selected students for in-depth interviews where they were asked questions about scientific theory and practice. Although the surface descriptions of scientific experiments and theories was equivalent across the different types of laboratory designs, the students in the research-based design "described experiments with more scientific purpose in mind, described theories from a more informed scientific perspective, and incorporated their own experiences into their descriptions of creativity in science" (p. 66). This personal identification with science, and the culture of science, is likely part of the socialization [209] process that brings new people into the discipline [11]. Weaver *et al.* [223] also report that research-based curricula result in increased interest in science and a greater sense of having "done science." In their summary of the existing research in the biological and life sciences, Auchincloss *et al.* [174] noted a strong but inferred relationship between CURE and regular undergraduate research experiences, themselves, and in addition they identified large gaps in the knowledge base for understanding how these experiences affect student learning.

With these sorts of potential gains at stake, changing the laboratory instruction program is a difficult and challenging task. In a national survey of faculty from 279 institutions, representing a broad array of instructional settings, Spell *et al.* examined why faculty members define authentic research experiences for classroom settings (experimental design, data collection and analysis), the degree to which these had been integrated into these programs (low), and the perceived barriers to their implementation (faculty time and resources) [224]. Brownell and Tanner [225] also hypothesize that the professionalization of academic scientists might well create tensions in their identities, putting efforts in teaching at odds with the norms they intuited during their training.

In shifting to a first-year organic chemistry course that is built explicitly on literature-based testing, students in a parallel, traditional general chemistry course showed differences, over time, with respect to the organic chemistry students on motivation and learning strategies measures [84]. Using the Motivated Strategies for Learning Questionnaire (MSLQ [226]), students in the organic chemistry course perceived a higher task value and intrinsic motivational orientation than their peers in the general chemistry course, while at the same time a lower sense of self-efficacy and higher test anxiety. Similar to the results in the research-based versus traditional laboratories, the organic and general chemistry students showed the same level of use of surface strategies in their learning, while the organic chemistry students also responded with using higher levels of deeper learning strategies. All of these trends are consistent with students who are in a more challenging environment, but who also recognize the higher value of the work.

Reading and understanding the primary literature is another enculturation feature for bringing new students into science. In studying a group of first-year university students in a life science program, Lacum *et al.* [159] observed that the design of the assignments was critical for student success. First-year students had a difficult time, relative to more experienced scientific readers, in identifying conclusions and the salient grounds for a given argument. This result mirrors that of Oliveras *et al.* [167], where students who read newspaper articles also had a more difficult time identifying both purpose and evidence than more sophisticated readers did. In both these cases, the assignments would benefit from breaking down the reading into explicit points of peer discussion, such as a milestone assignment where the students simply address “what is the writer’s purpose?” or “what is the writer claiming?” and then another one, after these discussions, that asks them to consider “what is the evidence that is used to support the claim?” (and then: “does the evidence support the claim?”).

9.3.6
Student-Generated Instructional Materials Promotes Metacognition and Self-Regulation

At the present time, metacognition represents our best understanding about why Flora is an effective learner [227]. She understands her strengths and weaknesses as an individual and has developed ways to exploit the former while compensating for the latter; she understands the tasks in front of her, understands what the underlying purposes are, and understands how to construct a reasonable pathway to the destination; she is aware of multiple learning strategies, how to use them effectively, and how they intersect with her own skill set; and she knows how to monitor what she is doing and how to evaluate where she is along the way. In designing an ideal learning environment for Flora, an instructor should provide both the necessary access to the knowledge that is needed and plan a set of experiences that allows her to deploy these skills in a meaningful way [228].

Student-generated instructional materials are an ideal way to encourage the development of metacognitive skills precisely because the learner is given a strong and familiar purpose: how to design effective instruction for one’s peers that causes a learner to examine deeply her own learning in a reflective and responsible way. The construction of simple multiple-choice questions with no embedded feedback, which might be the least complex version of this practice, results in higher student engagement and increased academic performance [229].

In a study where students designed electrical circuit problems for peers, whose artifacts were examined along with transcripts from semistructured think-aloud sessions [230], subjects not only drew upon their prior knowledge in appropriate ways, but “when thinking about alternatives (to provide feedback to peers about errors), subjects reflect on the procedure for the solution and think about possible mistakes that can be made … when thinking about mistakes, subjects seem to realize better what they themselves used to do wrong.” In addition, when addressing more complex computational problems, the subjects “did not just write down what they knew, but tried to organize it in such a way that it would be understandable” (p. 870).

Using content analysis of student-generated podcasts, in addition to examining transcripts of focus-group interviews, McLoughlin *et al.* [231] studied the levels of reflection and metacognition being used by five students who created supplementary audio (podcast) materials for beginning students in an information technology course. The metacognitive features they found in the student discourse included incidences of self-knowledge, task knowledge, strategic knowledge, and self-monitoring. As one of their subjects put it: “You’ve got to learn how to communicate with other people and understand them and you’ve got to learn how to get that across … ” (p. 7).

9.4
Conclusions

Metaphorically, Bereiter’s caricature of Dora, who sees education as a game of information rely and test-taking, also represents the challenge of school for school’s sake. Dora does what is necessary to pass the test, and moves on to the next hurdle of school work that she perceives is being put in her way. Flora, on the other hand, is building toward a time when she is not in school, and when she will be called upon to learn, and to apply what is learned, in the real world of her career choice. The distinctiveness of a university education [208], to build upon prior knowledge and develop discipline-centered conceptual understanding, to enhance and diversify the ability to learn, and to promote the attitudes, values, and beliefs of a future professional [207], includes the self-conscious need to move students from school-based homework to a more highly contextualized kind of work we are calling *Real Work*. *Real Work* is not only more characteristic of real-world tasks but also aims at developing the skills and habits of mind that are needed in the real world.

Unfortunately, the momentum in higher education has been drifting toward a “homework” mentality. Twenty-five years ago, Charles Sykes’ polemic, “Prof-Scam,” [232] which included the claim that academic standards were fraying, was easily ignored. Today, well-considered criticism is mounting from the inside. In 2010, Hacker and Dreifus [233], backed by considerable investigate prowess, returned to many of the themes raised by Sykes, particularly the lack of a strong, intellectually driven agenda for advancing the education of students at many of the institutions they examined. About the same time, Arum and Roksa [234] advanced an even stronger indictment, backed with considerable data. Nearly half the students in their sample did not develop the higher order skills that one expects in college-educated students, with a bit more than a third failing to do so even by the end of their university experience. Derek Bok, in a more recent and significant analysis of higher education in America [235], provides a balanced and optimistic view that change can take place, but he is clear that improvements in the quality of undergraduate education need to occur, and that there has been a slow decline characterized by incoherence and a reduction of standards.

In this chapter, we started with two related frameworks, authentic learning and situated learning. These frameworks are compelling precisely because they presume education derives from a focus on real-world skills, needs, and tasks, and is governed by the dispositions of the disciplines and the mastery of faculty instructors who derive intellectual strength from the depth of their understanding [11]. We have anchored the attributes of designing *Real Work* on solid practices that faculty instructors have demonstrated result in high quality values-based outcomes. Every example, for instance, of integrating structured, peer-led work, where students must explicitly deal with learning and then teaching what they know, results in higher achievement [216]. While the evidence does not always support deeper understanding and higher order learning, there is a preponderance of evidence for the general benefit of peer-led work, and the examples allow us to understand what might be necessary (e.g., careful training and consistent monitoring of peer leaders) to avoid the nonproductive results (e.g., some leaders still default to telling rather than facilitating discussion) [112].

Every instructional setting is different. Students range from teenagers, leaving home for the first time and living in a university residence, to mid-career parents with full-time jobs. Faculty roles are equally broad. The application of the *Real Work* attributes is going to be governed by creativity, adaptability, and compromise on the part of both students and instructors. Varma-Nelson has demonstrated that virtual group interactions for cPLTL retain many of the critical features of the face-to-face version (P. Varma-Nelson, private communication January 17, 2014) [132]. Classroom undergraduate research experiences can be full-fledged, multidisciplinary projects [175] or they can be the combinatorial optimization of an existing procedure [135]. Other changes, such as using student-generated instructional materials, probably rely on the willingness of an instructor to relinquish direct control over every learning resource in favor of directing and supervising the construction of materials that might not be as polished as those of an experienced instructor, but for which the construction might provide students with a uniquely valuable learning situation.

As a discipline, chemistry offers a few advantages for developing *Real Work* compared with the other sciences. A great deal of the primary literature, including experimental work, is accessible to beginning students. The more accessible the material is, the more deeply engaged students can be when participating in peer review and critique. Similarly, transforming information from original sources into student-generated instructional materials relies on the depth and degree to which students understand those sources. *Real Work* also generates artifacts that can be studied, and puts students into settings where they can be observed doing activities that reveal their internalization of disciplinary dispositions and display their learning strategies [197]. Thus, as illustrated throughout Section 9.3, those who are interested in evidence to support a claim for higher level learning and/or conceptual understanding can do so [236].

Real Work can restore and invigorate a post-secondary education in ways that Slavich and Zimabardo would define as transformational [207]. *Real Work* makes it less likely for Dora to slip under the radar as she relies on the rote, retention, and recall methods that have worked for her in the past. Flora is anticipated to thrive in a *Real Work* context, and she needs to be engaged to help Dora change her approach: because designing *Real Work* draws from the disciplinary expertise of an instructor, and one of its greatest promises is to energize the link between research excellence and teaching excellence, on which the historical strength of our system of higher education rests.

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