The Role of Written and Verbal Expression in Improving Communication Skills for Students in an Undergraduate Chemistry Program

Brian P. Coppola
University of Michigan, Ann Arbor
Douglas S. Daniels
University of Michigan, Ann Arbor [1]

Thought Takes Shape Through Expression

Proofreading, editing, and critique, the customary assessment tools scientists use to evaluate professional journal articles, grant applications, and any other writing, can be applied equally well in introductory science instruction. Such feedback is, in fact, crucial to growth and development. When learning anything new, students and faculty alike rely heavily on sources other than themselves ('external editors') to assess their understanding as they develop self-assessment skills (or 'internal editors'). Although they rarely describe it in these terms, faculty nonetheless assume that students have developed and refined their internal skills by the time they take examinations and write term papers. Unfortunately, science instructors traditionally provide little meaningful assistance or rationale for students to get to that point. This is in part because we faculty have already developed and deploy our professional skills so tacitly. To a degree, individuals who become faculty members probably follow paths of least resistance, the ones along which they were successful by virtue of their 'natural aptitude'. What some instructors intend to be their best advice to students can be wholly inadequate if it only reflects on the surface aspects of what they did as students: "do lots of problems," "write lots of prose," "sit alone and wrestle with the ideas."

One of the things we faculty do quite naturally in our professional lives is to rely on external input. Having developed any idea to whatever limit we are able to achieve sitting alone in our workplaces with our internal editors and our reference sources, we next try out the ideas on

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[1] Current address: *Macromolecular and Cellular Structure and Chemistry, The Scripps Research Institute, La Jolla, CA 92037*

our colleagues. Expressing our understanding to others is always a teaching activity since we are revealing our interpretation of some aspect of the world to another individual, testing the interpretation against another's point-of-view. Faculty share a common experience that they describe in familiar terms: "I never really learned it until I had to teach it." Perhaps what we also mean is that we actually think about our ideas in new ways when we are consciously aware of the fact that we need to describe them to someone else. In writing as well as speaking, attention to the needs of the audience is critical to clarity in the expression of meaning through the use of information (*1*). Learners learn differently, perhaps even more effectively, when they anticipate the need to express their understanding to someone else. For students, the most common example of this type of anticipation is in preparation for a written or oral examination. This perspective is not at all limited to expository writing and speaking, the usual modes of expression in the physical sciences; revealing internal perspectives represents +expression+ regardless of its modality, and does not favor writers and orators over thespians, pianists, painters, ballerinas or chanteurs.

The concept of expression is not limited to cultural discourse. In the late 1950's, biochemists needed to describe their new ideas about the transmission of genetic 'information' (mediated by DNA and RNA) and the construction of its corresponding 'meaning' (in the form of proteins, biochemical and physiological phenomena). The terms used by Jacob and Monod (*2-4*) have persisted in the biochemical jargon: *transcription* (for the appearance of DNA's genetic message in RNA, which also includes the terms 'proofreading', 'editing' and 'reading frame'), *translation* (for the appearance of a genetic message in a different language, that of proteins) and *expression* (an old biological term that refers to how genetic information is manifested, or 'understood', in whatever matrix originates it). These terms were drawn from and intended to reflect the metaphorical context of language with which they are naturally associated.

Maasen, Mendelsohn and Weingart have outlined the prominent use of metaphors shared between sociological and biological cultures (*5*). We find Dawkins' notion of 'memes' quite philosophically compelling (*6-8*) as a way to think about the transfer of information, the construction of meaning, and the process of learning (*9-10*). As a unit of cultural information, a meme sits at the analogical level of a gene. In our view, the term memetics, which has been recently coined (*11-13*), points to underlying processes by which cultural information is transferred, including information such as the ‘culture’ of chemistry or the process of its intellectual pursuit. Formal education, as a constructed tool, is an activity in memetic engineering. Like genetic engineering, memetic engineering is a technology, a product of human design and invention that results from an understanding of a natural process: learning, in this case. In its fundamental metaphors (*14*), the rhetoric of genetic transfer (transcription, translation, expression) has already and unknowingly borrowed from memetic transfer! We see this view as the closing of a circle, where the cultural world is reintroduced to physical world (*5*, *15*).

Inasmuch as we recognize the indispensable role that *transcription* plays in education, we readily acknowledge its limited utility in the development of critical skills. Understanding relies strongly on the constructivist (*16-19*) notion that learners *translate* their current understanding in the context of their prior experience when they need to integrate new information. Ultimately, it is the *expression* of a ‘teacher’s’ understanding that is perceived by a ‘learner’. What we expect from a virtuoso pianist is an expression of mood or emotion that this maestro has translated from a transcript of lines, bars, note symbols and clef marks. We would be surprised, disappointed and uneducated if this pianist were to simply hold the sheet music out to the audience and exclaim, “Isn’t that just beautiful!” As learners, for example, we appreciate Peter Schickele’s (‘P.D.Q. Bach’s’) musical ability as well as his lessons precisely because he can be within the performance and then in an instant be standing alongside of it, guiding his listeners in the composer’s art. The less experienced we are with interpretation, the more appreciative we are when an artist steps outside of a performance and draws our attention to meanings that might escape our more naive perception. Teaching is analogous to such a performance where naive learners develop their own abilities to express their knowledge. The processes that underlie preparing for a successful act of expression not only rely on transcription and translation skills, but also the relationship between knowledge of the subject matter and its connection to how its understanding can be expressed; that is, a performance resulting in memetic transfer.

Collaborative and Cooperative Learning Require Expression Skills

We all participate in a variety of groups as part of our daily lives, from families to social and work communities. As chemists, we are part of our colleagial departments, our professional societies, our research groups, and so on. In graduate and undergraduate school, some of us formed peer study groups in response to the demands of those other groups that we were a part of: our formal courses. We know we are not unique in this. The popular culture, at least, is filled with portrayals of medical, law, and business students who must divide responsibility for learning a daunting amount of course material and who then teach one another as a part of their learning. Graduate research groups in chemistry are generally highly structured by their research directors where community issues are involved (group meetings and assignments, shared equipment, and representatives who obtain specialized skills such as crystallography or mass spectrometry), but move towards a less authoritative structure when developing individual initiative is the goal. Individuals depend on (and learn with) one another in all kinds of educational situations. In order to emphasize this idea, Bruffee (*20*) advocates the use of a phrase attributed to John Dewey: “living an associated life.” As Bruffee describes it, formal education in America has been based on a philosophy of associated learning since at least the time of Benjamin Franklin. We all live and learn in an associated way. Differences in interactions vary according to the nature of a group’s structure (and sometimes, although not as often, to an individual+s degree of dissociation from the group).

The current renaissance in promoting structured group learning as a part of formal post-secondary coursework in science is approximately 15 years old. It is an outgrowth of recommendations for engaging students in more “active” (as opposed to “passive”) learning environments (*21*-*24*) as well as of a great deal of pioneering work done in undergraduate engineering education (*25*-*28*) and in the precollege “Cooperative Learning” movement (*29*, *30*). Structured peer group work has been a constant feature in disciplines that involve a great deal of writing, where there is an expectation for students to learn from one another. Not surprisingly, chemists have a long tradition of designing group laboratory experiments for undergraduates (*31*-*37*), even if they are used infrequently and do not dominate laboratory textbooks in the same way that lists of individual exercises do. Before 1980, published examples of group work in chemistry lecture courses are rare, although noted educator Frank C. Whitmore described an example as early as 1925 (*38*). The current cycle of designing and using group work is defined by the introduction of the terms *collaborative learning* and *cooperative learning* (*20*, *39*), which have been embraced by individuals in and beyond the chemical education community (*40*-*55*).

Neither "collaborative learning" nor "cooperative learning" are intended to be interchangeable euphemisms for "having students work in groups." Individuals are still wrestling, however, with the distinctions between and usage guidelines for these terms (*20, 27, 39, 56*). We have also added our voice to this discussion (*10*, *54*). We have posited that many have framed their ideas on the false assumption that cooperative and collaborative learning represent a dualistic system (comprised of opposites, where characteristics of one attribute can be used to define the other) rather than a synergistic one. To resolve this, we view the issue of how group work is structured as the context in which separate cooperative and collaborative dimensions arise. Collaborative issues are related to the organization of the "labor.". *Collaboration* relates to the structure of the knowledge that is needed to accomplish a given task, and the benefit that comes from individuals organizing themselves so that responsibilities within a task are matched to specific skills. The organizational opposite of this collaborative sense is a "commutative" one (or perhaps "equalitarian" is a better word choice) where each participant is (can be) held equally responsible for every part of a task or outcome. *Cooperative* issues arise that are related to how individuals "operate" in group situations. Cooperation versus competition is a familiar dualism that is used to characterize the spectrum for how individuals operate within a group.

Specific examples of both cooperative and collaborative learning tasks can be found in the chemical education literature or adapted from other disciplines. As chemists and chemistry instructors in our own classes, we are ultimately responsible for deciding which of our instructional goals are best suited to what sort of teaching method (hence the importance of a rational and well-articulated set of goals). The cooperative tradition embodies an externally imposed structure. The collaborative tradition is based on the valuing of an internally developed structure and the contributions from individuals. The difference in outcomes from tasks structured to reflect these different values and skills represent the kinds of effects that all instructors should be interested in promoting during the course of a student's education. Do we want students to be well-informed about the existing dogma? Do we want them to be able to make improvements within the context of existing knowledge? Do we want them to achieve in ways that go beyond our traditions that are nonetheless founded on the strengths of what has come previously? The answer to all of these questions, naturally, is yes. As instructors, we need to assess the desirability of a given kind of outcome with respect to our instructional goals when designing educational tasks. If we want our students to achieve in a particular way and not in another, then the structure of the task plays a significant role. Indeed, the most sophisticated skills to develop for doing group work are (1) how to match a problem with the kind of organization that is most effective, and (2) how to turn an existing yet ineffective organization into a more productive one. In education, advocates for group work have provided a blueprint for enabling students to develop all of these skills by carefully considering the effects of group structure, task design and the synergistic dimensions of collaborative and cooperative learning.

An Example of Progress in Practice: "Who Has the Same Thing as I Do?"

As faculty, graduate and undergraduate members of the chemistry department at The University of Michigan restructured the undergraduate chemistry curriculum, we also took a fresh look at the nature of the laboratory experiences that would accompany the new courses. In creating these courses, we wanted to capture the essence of a research experience: the design, implementation and evaluation of an experiment with an uncertain outcome. This plan allows students in an introductory course to construct their own understanding of a solution to a problem without requiring instructors to direct 2500 research projects a year with very inexperienced individuals (an intimidating notion!).

We devised the following criteria as guideposts for our thinking about the first term laboratory course.

● **Make problems comprehensible.** If student learning is to be subject-centered and based on prior experience, then the tasks must be comprehensible to the novice. One common complaint from students in traditional laboratories is that they are simply following directions and not engaged in activities with any intrinsic meaning to them.

● **Embrace imperfection and promote improvement.** We are committed to let experience lead, whether it is observing solubility phenomena or recording an infrared spectrum. We want students to experience phenomena and to have a chance to develop their abilities through repeated practice. An hour of careful discussion and preparation for what is to be observed is a symptom of an upcoming laboratory activity that a student is not yet ready for, or for which an instructor is taking too much preemptive responsibility. Students should not be expected to master an unfamiliar activity the first time that they do it threatened with the disincentive of a grading penalty if it is not done correctly.

● **Use techniques as tools to solve problems.** We wanted to emphasize the variety of techniques that chemists use routinely in order to collect information about substances. To these ends, we see no purpose in any discussion of "cookbook versus discovery," because this is a false dichotomy. Cookbook and discovery are not opposites on a linear spectrum, but rather they are related to each other on intersecting axes. Chemists generally begin with known procedures and strategies (cookbook) in order to make discoveries.

● **Promote collaborative laboratory work.** Whereas cooperative learning strategies tend to create environments for group responsibility in task management, the process of collaboration maintains individual responsibility within any group effort. We hold that a collaborative learning task promotes individual responsibility within the context of a group task that is solvable only by the contribution of each participant.

Collaborative Identification of Unknown Materials

Whether by consulting a reference text or using our recall of physical, chemical, and spectroscopic properties, we compare the data we collect in lab with some set of standards in order to answer the question "What is this?" Rather than provide inexperienced students with an explicit algorithm for making an absolute identification of a substance, we have taken the core of this activity and created a problem in relative identification that is at once a simple, honest inquiry and a vehicle for developing technical and communication skills.

Who has the same solid that I have? On the second week of college, students in each section of a 22-student *Structure and Reactivity* laboratory course are presented with a box of 30 vials, numbered in sequence, that all contain a few grams of a finely powdered white solid. In addition to referencing parts of a techniques manual where melting points, solubility tests, thin layer chromatography, and infrared spectroscopy are discussed, students are provided with the following information (*54*, *57*):

> Most scientists collaborate and cooperate with each other in making scientific discoveries. Modern science involves a lot of team work. Many times, also, the same discovery is made at the same time by different scientists in different parts of the

world. They then have to exchange data and samples of chemicals or biological specimens to prove that they are indeed dealing with the same substances.

In this experiment you will be attempting to solve a puzzle together with your classmates while you learn basic techniques used for the analysis and identification of organic compounds, as well as getting to know your classmates. We hope that this will be the beginning of a habit of working together in learning your lecture material as well as in the laboratory.

The puzzle is simple. Chemists define substances on the basis of an accumulation of observable properties. For example, when we say “water,” we mean “that clear, colorless, odorless liquid with a boiling point of 100° C, freezing point of 0° C, a density of 1 g/mL that dissolves substances like salt, that upon electrolysis gives a mixture of hydrogen and oxygen gases in a definite ratio”...and so forth. Using our molecular model of matter, itself a result of the collective imagination of chemists, we say that “water” is “H_2O,” and we mean to indicate that whole accumulation of information behind that simple symbol. Thus a fundamentally important skill is to accurately determine and compare the physical properties of substances.

You will obtain a sample of an organic solid. You will determine properties such as its melting point, its infrared spectrum and how it moves on a thin layer chromatography plate in one or more solvent systems using one or more visualization techniques. *Your goal is to find the other students in class who have the same compound as you do.* Comparisons of different samples may be made in a number of ways: (1) by spotting the samples side by side and co-spotting on a TLC plate; (2) by comparing solubility and appearance of the samples; and (3) by taking melting points and “mixed melting points,” a melting point of an intimate mixture of the two compounds. If the two compounds are identical, the mixture will not melt any lower than the individual samples do. If the compounds are different, one will serve as an impurity in the other. Impure substances melt at lower temperatures than pure samples do.

Your laboratory section should work out a method for sharing and reporting your sets of individual data. Once you have identified yourselves with a particular compound, the group should affirm the predictions about who has the same

> substance, and also confirm that there are no others in your lab room who belong with the group.

We provide ten sets of triplicates in the solid samples, which generally include a variety of aromatic hydrocarbons, ketones, and carboxylic acids. The most important practical aspect of setting up this laboratory is to ensure that the identification is based on the experimental data that are collected by the students. The activity is made less honest in a number of ways, so the following caveats should be kept in mind: do not use coding schemes that can be decoded, do not give out lists and samples of possible substances too early, do not give the lab instructor the master list (alternatively, hide yours!), do not permit colored substances and do not leave solids unpowdered. By using melting points (and mixed melting points), thin layer chromatography (with co-spotting), and solubility tests (5% aqueous hydrochloric acid, 5% aqueous sodium bicarbonate, acetone, and water) a class can easily group themselves and double check their observations within a few hours. One of the questions that spontaneously arises every term is what constitutes a valid comparison. The melting point data only group together rather than occur with exact duplication, so we always hear a version of the following: "Is 156-7° C on my thermometer the same as 152-5° C on yours?" A very productive iterative cycle occurs as the need for reproducibility causes students to revise their original reports in the context of new information. The experimental techniques are clearly seen as tools by which data are collected and from which a simple question can be answered.

Another unique aspect of organizing an activity around the "Who has the same substance that I have?" question is that collaboration requires communication. As a group, students in a lab section must establish procedural norms for collecting data, such as what proportions to use for solubility tests, and for reporting and exchanging data, which is required in order to solve the problem. On any afternoon, we can have eight sections of the *Structure and Reactivity* laboratory course operating with eight different sets of procedural standards and communication strategies. Finally, this is a *collaborative learning task* , as described above. After the entire group has established its common experimental procedures, individual students are responsible for collecting data from their own substance. As the information flows from individuals to the whole classroom community, smaller collaborations occur spontaneously as subgroups begin to gather around a common substance, along with the need for building consensus about the properties of the substance they suspect they share.

For the next laboratory period, the instructions are geared for taking the relative identification to an absolute one:

> Once you have identified yourself as part of a group of students who all have the same substance, you should deal with the identification of that material. Consult a list of possible substances that your TA has in order to begin to make this decision. Samples of these compounds are available for performing TLC, melting point, and solubility comparisons between your unknown compound and the possible knowns. You should also record infrared spectra of your solids in order to make a judgment about what kind of functional group classification your compound falls into.
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> When you think you have an idea about what compound you have, you should also select an appropriate chemical derivatization method for that functional group and prepare it. You can use both your unknowns and the known compounds (for practice) in this procedure.

The collaborative identification blueprint works for developing a variety of laboratory skills. We have used this technique with liquids, solutions of different concentrations, and as a novel modification of the traditional density exercise.

Extending collaborative activities to other courses, other grade levels, and other subjects.

As described above, we have used collaborative activities in many places in our curriculum. In addition to the preservice teachers course and the high school class, we have also used “Who has the same solid that I have?” for five years as part of outreach programs for middle school and high school students who visit our department for either a day or a week. Precollege students, using only solubility observations and melting point determination, routinely solve the solids problem in about an hour. For groups of very young students, we have simply placed common objects inside of a plastic film canister and had them answer the relative identification question based on comparisons of sound and touch. An imaginative adaptation of this idea was done by one of our colleagues in the mathematics department. At the beginning of an introductory math class, every student in the class was handed a slip of paper on which a set of 4 numbers was written. These numbers were sequential portions from a variety of different series; the students' task: "Identify who has numbers from the same series as yours." Differential discriminations are made by individuals in every discipline, of course. Some of our other colleagues have reported their own adaptations of this idea to us: in art history ("Who has a painting from the same period that I have?"), in psychology ("Who has the same personality classification that I have?"), and in journalism ("Who has paragraphs structured the same way that I have?"). The collaborative identification of substances is a simple blueprint for any activity where related samples can be investigated by an appropriate technique. This activity gives a way for instructors to demonstrate the relationship between collecting experimental data and drawing conclusions, as well as how to make and evaluate comparisons. Students are also required to create procedural standards and to communicate within the context of a scientific problem in a natural and need-based manner. Collaborative identification is an honest inquiry that encourages students to combine technical and social skills, a goal of many reform-minded educators.

The Performance Studio for Expressing Science

We think it is useful for instructors to realize that we ask our students to teach us on our exams. This is a familiar idea to many instructors who understand that students teach us something about how effective our instructional practices have been, how well the intended lessons have been learned, in addition to a host of other lessons about learning in general (*58*). But, if we instructors design examinations to be most useful for the learners as well as for us, then we must also ask students to take on the role of instructors in our discipline. We must provide them with an opportunity to think about chemistry in a way instructors have already acknowledged to be the most useful: "I never really learned it until I had to teach it." Examinations are always structured for this role-reversal at any rate, differing only in how well the structuring has been done rather than in the presence or absence of it. In all cases, whether an exam is in written or oral format, an instructor takes on the student role as questioner and learner, while the student is the one who provides answers. Yet honest opportunities for students to build the skills for this role-reversal are not provided except at the exams themselves, and faculty tend to adopt the role of arbiters who judge rightness and wrongness. By pointing out to students that during examinations they are assuming the teacher's role, we allow them to confront the need to learn how to express their understanding before the examination. We have actively promoted ways for students to practice their teaching (hence, expression) skills before the examination.

Our colleagues in disciplines that more openly acknowledge their reliance on developing skills for expression (writing, art, dance, theater) all rely on the performance studio in their instructional design. The studio is a place where the desired skills can be displayed to a peer group of learners, usually under the guidance of a more experienced individual who critiques as well as organizes peer review, and generally after some amount of solitary preparation has occurred outside of the studio (wrote a story, filled a canvas, or learned the lines). A great deal of high-value learning takes place in the studio because every participant has done something about a common task (write a story, fill a canvas) that carries the results of their individual efforts. Where is the comparable 'performance studio' for chemistry learners? Laboratories should fulfill this role, but there are many reasons why this is not true in practice. In any event, regardless of the design of laboratory courses, skill-building with those activities seems too far from the expected mode of expression on an examination.

We have, however, created an option for introductory science students that draws from the principles outlined above. In our structured study group program, a cohort of 120 first-year undergraduate Honors students, while taking standard coursework and examinations in a 1200-student course, earn their Honors credit by participating in extra weekly 2-hour sessions that are shaped, metaphorically, along the lines of a 'performance studio' in the Arts. Assignments, in the form of common (not identical!) tasks, are subjected to peer presentation and peer critique facilitated by upper-level undergraduate leaders. Unlike simply directing students to work in groups or only providing them with problem sets, both of which are productive and engaging (Hurley 1993), students in the structured study groups follow a detailed curriculum that helps them to develop the kind of skills that we believe are attached to a deep mastery of the subject matter in a format that encourages the students to also develop their more general learning skills.

During each session, the meeting time is typically divided between a number of activities. Each participant brings a duplicate set of his or her written assignment from the previous week. These assignments generally involve the creation of examples within a given context. In the very first assignment, they pick a C_{10}-C_{13} molecule from a chemistry journal (after learning, in their session, how to decode line formulas, what journals are, where they are found, and what proper citation format looks like) and are directed to construct 5 rational examples of molecules with the same formula. They then propose rankings for their created molecules based on 3 of 6 properties, including, for example, magnitude of dipole moment, boiling point, and solubility. Later, a typical assignment might be to find an example of an S_N2 reaction in a chemistry journal and format it as a quiz problem appropriate to the level of the class. The students are always directed to provide a brief statement that puts the reaction in context, a copy of the journal pages from which the example is derived, and a properly formatted citation. At the beginning of the session, the students submit one copy of their work to their leader, and the other copies are redistributed to the class. One or two rounds of peer review follow. The reviewer does not correct the other student's paper, but rather answers a set of factual questions about the others' work: does the molecule or reaction fit the prescribed criteria (yes or no?); is the format and information appropriate to the level of the class (yes or no?); is the citation formatted correctly (yes or no?). During this time, the discussion within the group is free-wheeling, and it is the time of greatest learning for the students. Although the only duty is to mark off a "yes" or "no", the first round of peer review can take up to an hour. Only when faced with reviewing another+s work can the student deal with issues that were either incorrectly understood or that simply did not occur to them. These students have a structured opportunity to make, recognize, and correct their errors before they get to an examination. After the reviewing is completed, the reviews and the unmarked papers are returned to the originator, and he or she has a chance to decide whether any corrections are needed. This second set of assignments and the reviews are collected, and they form part of the basis for the leader's evaluation of the student's performance that day.

Strands of advanced topics also comprise part of the curriculum for the groups. During the year, spectroscopy, bioorganic chemistry, and work involving Frontier Molecular Orbital theory (electrocyclic, sigmatropic and cycloaddition chemistry) are introduced over the course of the group assignments. Some of these activities can be structured using practices that are common in language composition courses. During the last month of the first term, for example, the students examine 2 or 3 short publications written by a departmental colleague in order to develop a set of questions that one might ask of the author. Over the 4-week period, students review and refine written questions submitted by their peers for both content and clarity. At a last meeting attended by all of the group members, students meet with this author after having studied his or her writing, and then ask questions from a set selected during prior group work. Case studies in research ethics are included in the second term's curriculum and allow us to study much about scientific practice in addition to factual information. Casebooks appropriate for undergraduate and graduate instruction are beginning to become available. In chemistry, Kovac (*59*) has produced *The Ethical Chemist*. The Association of American Medical Colleges has prepared a complete handbook for instruction (*60*). Casebooks for other disciplines are being developed at the Poynter Center for the Study of Ethics and American Institutions (Indiana University). During the last month of the second term, the students produce their own ethics cases, usually drawn from their experiences at the university. Over a 4-week period, three cycles of editing and peer review for both the content and the composition are included with the weekly group meetings.

While expression and peer review skills have been educational objectives for the student participants, the educational experience for the 7 or 8 undergraduate group leaders has also been profound. They, in effect, participate in an informal course in classroom practice and pedagogy every week during their regular leaders' meeting. The level of engagement and excitement that has been generated in this group of students, who are themselves in the process of making career decisions about graduate and professional schools, is quite extraordinary, and may be one of the most important outcomes of this process. Instructors at any level of experience will appreciate the most common reaction of our leaders during the first few weeks: “Boy, this is *really* hard!” About half-way through the term, the group leaders also develop the ethic of what they call ‘active non-participation’. Their comments revealed that the teaching abilities of these student leaders evolved rapidly: moving the center of classroom activity from the role of “teaching to” their students to becoming authentic discussion facilitators in a group classroom. In large part, the tasks and the structure of the peer evaluation component encourage the leaders to shift into a more collaborative learning mode. Walters, and others, have reported similar outcomes for student leaders who assume authentic roles in the design and delivery of instruction to beginning students (*61*).

Conclusion

Our system of higher education sits in an uncomfortable position: it is both the tool and formal construct of disintegrated knowledge (*9*). Through the customary process of intellectual inquiry, disciplinary specializations have emerged and separated from one another...as have the specialists. In the name of progress, we educators direct and identify young learners according to our assessment of their aptitudes for pathways we define and (continually) refine. If thinking about unifying educational objectives is to be useful, then it is important to recognize this as a reunification, less in terms of 'integration' and more so of 'reintegration,' where we take advantage of our hard-earned depth of understanding to rediscover our common purpose of understanding and expressing notions about the world to each other.

The consequences of disintegration on science education have been profound. Traditional scientific training neither encourages nor impels its students to develop effective communication skills for groups outside of the discipline...and yet it is precisely this inarticulation that must share at least some of the blame for the general inability of the general public to appropriately assess and evaluate technical issues with which they are confronted. Progress has led to physical and intellectual isolation of many disciplines from one another within universities. Every year, this same progress contributes to the concern to 'cover' the increasing amount of factual subject matter in science. This emphasis has exaggerated the dispassionate, objectivist vision of scientific practice. Separation has slowly stripped away the clearly value-laden dimensions of science from formal science education. The existence of historical, philosophical, sociological, linguistic, and moral considerations, if not ignored completely, are minimized as significant arbiters in decision-making (*62*). When history does appear, it often does so in neatly isolated and easily neglected textbook side-bars.

One goal of our teaching in introductory courses at the University of Michigan then, has been to integrate the historical, philosophical and linguistic aspects of science with the factual information. We recognized very early in the process of restructuring our undergraduate program, which began in 1989 (*63-66*), that this would involve a greater emphasis on writing (and other forms of expression). This writing needed to be in both the common language and the unique semiotic systems devised by chemists, and that this would involve creating organized group learning and guided peer review within some fairly traditional course structures. Effective written and verbal expression, and its review, critique and refinement, sits at the core of making yourself understood. Every discipline needs its participants to communicate well both inside and outside of the professional community. As the intellectual disintegration of the academy leads to rhetorical separation and isolation, the need to communicate meaningfully only increases. By making these perspectives a part of our teaching, we find that we provide a rich array of entry points through which students can make integrative connections in their learning. By emphasizing the fundamental narrative (story-telling) aspects of science, we have had our best success in demonstrating to new learners that they can, indeed, participate too.

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