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Teaching from the primary inorganic literature: Lessons from Richard Andersen‡

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‡ This Perspective is dedicated to Prof. Richard A. Andersen on the occasion of his 75th birthday.

ABSTRACT
For many who passed through his classroom, Richard Andersen demonstrated how inorganic chemistry can be taught by incorporating the research literature. The Interactive Online Network of Inorganic Chemists (IONiC) through its website and summer workshops for faculty has supported the development and sharing of more than a hundred exercises or “learning objects” derived from articles highlighting research across the inorganic field. Faculty can adapt and implement these learning objects in their own classrooms to achieve goals such as demonstrating historical context, teaching course material via current research, and elaborating on the scientific process. Literature discussion learning objects highlight current and past research in inorganic chemistry and teach students both chemistry content and how the body of inorganic knowledge is constructed.

Dick’s teaching

> *The graduate organometallic chemistry class met in an unmemorable building at the foot of the scenic Berkeley campus. The graduate students walked cautiously into the room, greeted by a chalkboard filled with molecular orbital diagrams and literature citations. Professor Andersen finished up the last diagram and turned to the class. “You have to have been born knowing the molecular orbital diagram of ferrocene,” he chided. (J.L. Stewart, circa 1984)*

Richard Andersen’s graduate inorganic and organometallic classes were rich with data, alive with chemistry anecdotes, and most importantly, brimming with examples from the chemical literature. Teaching with the literature in this manner allowed students to trace the history of the key discoveries in inorganic chemistry and scrutinize the thinking of the scientists as those ideas emerged.

For example, in teaching about main group cyclopentadienyl compounds, Andersen started with Thiele's 1901 *Berichte* paper on the synthesis of potassium cyclopentadienide.[1] Then he moved through the rest of the main group elements reporting molecular structures and NMR results in detail, providing literature references each step of the way. In recounting cyclopentadienyl magnesium compounds, he described structures,[2] dynamic behavior,[3] synthesis,[4] and bonding.[5] He discussed the unusual solid-state structure of the calcium cyclopentadienyl compound, where calcium's coordination sphere contains two η^5-C_5H_5 rings, one η^3-ring and one η^1-ring.[6] He chronicled the debate between σ-bonding versus π-bonding in various cyclopentadienyl mercury compounds,[7-9] and a similar debate for the bonding in cyclopentadienyl copper complexes.[9-11] Dick's depth of knowledge and thoroughness could only be matched by his humor and irreverence when teaching.

Andersen's literature-rich approach to teaching has inspired several generations of chemistry faculty to teach in a similar manner. The Interactive Online Network of Inorganic Chemists (IONiC), a community of inorganic chemists, has developed over a hundred "literature discussions" that enable undergraduate students to learn fundamental inorganic chemistry concepts using current and historical examples from the literature. In this paper, the research on the efficacy of teaching with the primary scientific literature is reviewed, the implementation and promotion of literature discussions by the IONiC community is described, and examples of how to teach with the literature, including a new example from a recent Andersen paper in this journal, are illustrated.

Using the Primary Literature in Teaching - Teaching with Literature Discussions

Discipline-based education research across the sciences and engineering has, through empirical study, found that active learning strategies have a positive impact on student learning.[12, 13] Engaging students with the primary scientific literature is one such active learning approach.

There are many studies, primarily from the biology education research community, that show the positive impact of using the primary literature to teach science. By working with the scientific research literature, students gain both content knowledge and other science skills. Students start as novice readers, focusing on lower-order cognitive processes such as simple comprehension. However, with both guidance and practice, students become more expert, using higher-order cognitive skills that require critical thinking.[14-18] Studies show that reading the primary literature increases students' confidence in their ability to read, understand, and explain science and to critically review and analyze data.[16-26] Reading the literature also helps students better understand the nature and process of science and develop more sophisticated epistemological beliefs.[21, 26] It can also increase student interest and enthusiasm about course material.[20, 25] Increased interest and confidence, which contribute to increased student motivation, are important contributors to student success.[27, 28] The positive impact of these affective changes on student performance and long-term engagement in chemistry should not be underappreciated.

There are many different approaches to teaching with the chemical literature. Some faculty, like Andersen, deliberately link the examples in their class with specific experiments from the literature to provide a sense of the development of the field and the context of data. Other approaches include:

- using recent or classic examples from the chemical literature to illustrate concepts;
- using recent studies to pique student interest or show them how science impacts their daily lives;
- developing problem sets, exam questions, or in-class activities from the primary literature;
- using the literature to focus class discussions (vide infra).

In some cases, instructors devote their entire course to discussing scientific papers.[29-34]

Just like solving chemistry problems, learning to read a scientific paper is a skill that can be taught. It has been demonstrated that beginning students or novices read papers differently than experts.[16, 18] It is important to start simple and provide the appropriate supports or "scaffolding" to build student expertise over time. The teaching methods that document the greatest student learning gains focus on engaging students with the data presented in the paper.[20-22, 35-37] Other effective teaching methods include using jigsaw exercises where students dissect different parts of a paper in small groups then come together to reconstruct the paper,[12, 38, 39] having students respond to questions in a reading guide prior to a whole class discussion,[38, 40-43] or participating in a class-based journal club.[35, 44-47]

Teaching with the literature has been shown to positively impact student learning and motivation, help students understand the nature of science, and help students gain confidence as scientists. However, in a field as scientifically rich and broad as inorganic chemistry, how can instructors stay abreast of the literature across the entire field in order to be able to choose the most effective papers for student learning? Fortunately, there is an online resource that contains many well-developed examples from all of the areas of inorganic chemistry. Each example has carefully written questions to guide student reading and answer keys for faculty who might be stretching beyond their own area of expertise. These activities can be easily adapted so they can be incorporated into existing courses.

What is a VIPEr literature discussion?

The Virtual Inorganic Pedagogical Electronic Resource (VIPEr)[48] was built as an online "home" for inorganic chemistry educators—a place to share teaching materials and to build community. As of June 2018, the VIPEr website contains approximately 950 learning objects (LOs) or small units on various topics for use in an undergraduate classroom as well as over 500 discussion forums where topics range from syllabus construction to laboratory practice. These learning objects are developed, uploaded, and used by the nearly 1200 registered faculty users, although most of the site content is available without registration. In 2017, for example, the site had approximately 18,500 total downloads, or about 50 downloads of teaching materials per day.

One of the learning object (LO) types we emphasize and promote is the literature discussion LO. Like Richard Andersen's classes, we hope to bridge the gap between what can be found in most inorganic textbooks and the primary literature. These literature discussion LOs pair a recent (or classic) journal article with carefully crafted reading questions that guide the students' engagement with the text. Additional notes for implementation might describe how the paper can be used to teach one of the core concepts in inorganic chemistry or particular areas where students often need assistance in thinking through the paper's arguments. Each learning object contains suggestions to assess student learning, examples of student learning results, and an opportunity for other implementers to comment. Faculty thus become facilitators in a student-centered instruction model that helps students see important inorganic chemistry concepts illustrated in modern chemistry. With the cycle of assessment and review, questions and activities can be continuously improved. Currently there are 133 literature discussion LOs on the site, and IONiC workshops have trained 112 faculty members, graduate students, and postdocs interested in becoming faculty members in the use of VIPEr, active learning strategies, and incorporation of the primary literature into the classroom.

The primary goal for most faculty who incorporate literature discussions into their course is to help students learn the course content. If an instructor wanted to teach symmetry and vibrational analysis, they would choose LOs that emphasize these ideas. For example, the LO called "The structure of an iron carbonyl compound by analysis of the IR spectrum," is based on an *Organometallics* paper. The LO's learning goals are to (1) determine the point group of two different molecules; (2) assign a reducible representation for the CO groups in these molecules; and (3) reduce their reducible representation and determine the number of IR active CO vibrations in the molecule. Rather than discussing book examples, the instructor could ask students to read the section on IR characterization of the complexes and assign point groups as homework.[49] Later, the LO's discussion questions that focus on group theory could be completed as an in-class activity, interspersed with discussion and short lectures for clarification as necessary. A related LO with similar learning objectives, such as "IR and Raman Spectroscopy of Cobalt Boronyl Tetracarbonyl, $Co(BO)(CO)_4$" could be used to assess student learning on a subsequent exam.[50] Instead of starting with how to derive irreducible representations and then only later relating that abstract process to real-world examples, this LO approach puts current examples at the forefront, motivating student learning with examples from the primary literature. Rather than add to class time, this literature-based activity would replace existing class activities.

In addition to teaching inorganic chemistry concepts, using literature discussion LOs helps faculty to develop student skills. Students develop critical thinking skills because they evaluate and analyze arguments. They also help students better understand the practice of science. LO discussion questions typically model a process one might use when engaging with an unfamiliar journal article. What does the abstract say the article is about? What context for the work can you find in the introduction? What do the figures suggest about the results? Reading more closely, what evidence do the authors cite for their conclusions? What would they (or the student!) choose to do next? Students see real examples of synthetic and spectroscopic techniques they are learning and read about techniques with which they are unfamiliar. Additionally, students become familiar with current, and sometimes historic, research and researchers. They begin to have a sense of the “family story” of inorganic chemistry and, if journal articles are paired carefully, they may be able to see how newer research developments are informed by prior work.

Teaching with literature discussion

The primary advantage of using VIPEr literature discussions is that they already have well-designed reading questions and answers, and they have been evaluated by an expert who determines that the questions are at an appropriate level for the undergraduate student classroom. Literature discussion questions provide extra support to help students through an article. An added benefit is that they assist instructors so that they can more easily teach current research in inorganic chemistry outside of their specialty area. The LO “Using Solid State Chemistry and Crystal Field Theory to Design a New Blue Solid,”[51] enables students to learn and apply crystal field theory in the context of a solid that has become a commercially available pigment. Non-solid state chemists may not be familiar with this research, but the LO enables them to show students how a fundamental inorganic concept such as crystal field theory can be applied to design new materials.

Each literature discussion on the VIPEr site includes a student handout with guided reading questions and a document for faculty that contains additional instructions and an answer key. The student handout is available to the public, but to view documents only for faculty, such as keys for literature discussion and problem set questions, registration on the site and verification of “faculty status” by the site administrator is required. The LO also has a link to the paper from the primary literature.[52] Each LO has a description of learning goals, student learning outcomes, implementation notes, evaluation methods, and a comment thread where those who have used the LO can post their comments.

The most common methods of using a literature discussion LO in a classroom include small group or whole class student-led discussions, or whole class faculty-led discussion. The questions in the LO are designed to be answered using the paper as the primary textual source. Some LO authors also recommend additional sources as part of the LO to provide deeper coverage of certain topics. Students frequently use their textbook and online sources to help with vocabulary or unfamiliar techniques. Many literature discussions are written with more questions than the authors would use. This is done so that individual faculty adapting a literature discussion can choose a focused set of questions that meet the specific needs of their class. Before beginning a literature discussion an instructor should edit the reading questions, selecting those that focus on the desired learning goals.

A typical way to start a literature discussion is to assign the paper as an out-of-class homework assignment. Students will read the paper and answer some of the questions; other questions may be reserved for the in-class discussion. Depending on your students, it can be important to let students know the expected time needed to answer the questions; students may skim the paper too briefly to just get the answers to the specific questions without incorporating the broader narrative, or they may spend too long reading every single word of the paper. Typically, the guided reading questions are then collected during the class period when the paper is discussed. However, students may be allowed to keep their responses and make corrections on their answers during the broader discussion. To differentiate pre- and in-class work, an instructor could hand out a blank sheet that students could use for additional notes or the student could use a different colored pen or pencil for in-class responses.

The in-class discussion is best moderated by students. In classes that are focused more on the literature, teams of students can rotate through leading the discussion from week to week. In classes where there are large student numbers or few literature discussions, a simple way to ensure student participation is to give all students a fixed number of tokens for comments and questions. Students are not issued a second set of participation tokens until after everyone has used their tokens. A Harkness diagram prepared by a student or faculty scribe is also a useful way to monitor and ensure participation by students.[53] Harkness diagrams provide a visual representation of the student-student interactions (asking and answering questions) occurring during the discussion, and can bring attention to students who are not contributing or to students who may be dominating the discussion. Another good practice is to use a scribe to take notes on the discussion. Since the scribe is taking notes on the key points, students do not need to be as concerned with missing things because they are participating. These can be shared through a course management system. If students are fully responsible and a scribe is used, it is possible to do a literature discussion in class even if the faculty member is away at a conference, though this would perhaps work best in an advanced classroom later in the semester.

By stepping out of the direct conversation, the instructor forces students to grapple with the ideas in the paper. This often leads to interesting discussions that would not be obvious to an expert in the field. Students often are critical of the writing in the paper, which allows for a discussion of good practices in written communication. Students often initiate discussions on the scientific process and how the research was done. This can be primed in the guided reading questions. For example, students can be asked if they think the experiments were described in chronological order. Some faculty let the discussion go where it may, but many prefer to take a more active role in guiding the conversation to avoid too much digression. When students have misconceptions or major misunderstandings, it is important to step in and correct them.

Student performance can be evaluated across several dimensions. Participation by students can be directly measured using the Harkness diagram or by the quantity of responses on the pre-class assignment. The answers to the questions can be graded for correctness, including both pre- and post-discussion components if desired. Finally, questions related to the literature paper can be included on a midterm or a final exam.

How to develop a literature discussion

Some instructors may prefer to develop a new literature discussion rather than use an existing one. They may find that existing discussions don't cover their learning goals, they may be excited about a paper and want to share it with their class, or they may want to highlight their own research and help it reach a broader audience.

The first step to developing a literature discussion is to identify the learning goals for the literature discussion. A paper might be selected to cover particular content or instrumentation; or it could be chosen because it has elegant arguments that help develop scientific reasoning; it prepares students to meet a seminar speaker; it illustrates a broader theme like sustainability, nanoscience, or the interdisciplinary nature of chemistry; it reviews ideas from across a course; etc.[54] Well-written articles that explain how the research is situated in the field, draw conclusions directly from data from multiple sources, rely on fundamental concepts in inorganic chemistry, and make a strong contribution to the existing body of knowledge are good candidates for literature discussion assignments.

To illustrate the development process, the authors of this paper collaboratively developed a literature discussion LO to celebrate the work of Richard Andersen.[55, 56] Work in the Andersen lab has focused on the synthesis and reactivity of f-block metal complexes. It was only fitting to choose one of his recent papers from *this Journal* as the source for the LO.[55] Whilst this is an excellent contribution from Andersen's lab, this report of pentamethylcyclopentadienyl compounds of *f*-block elements would be daunting for many undergraduate students to read. This collaborative nature of the LO development process was essential because most of the developers are not *f*-block chemists. Several group discussions were needed to ensure the authors were in agreement on the interpretation of the paper.

The practice of "backward design" – first determine the student learning goals and then develop the means for achieving them – is useful to develop LOs.[57] Because this LO was developed to highlight Andersen's work, it spans a range of topics in f-block chemistry, mechanism, and science practice. In the Andersen LO, most learning goals focus on chemistry content, such as predicting common alkaline earth and lanthanide oxidation states based on ground state electron configurations or explaining how calculated reaction coordinate energy diagrams can be used to make mechanistic arguments. It also includes elements of science practice; students should be able to describe how negative evidence can be used to support or contradict a hypothesis. Once established, these learning goals can then be translated into questions: "The most common oxidation state for the lanthanide elements is +3. Yb is unusually stable as both Yb(II) and Yb(III). Use electron configurations to explain why lanthanides are typically +3 and Yb(II) is unusually stable."

A good set of questions will be carefully aimed at the students' level. Many undergraduate students lack extensive background reading the research literature and prioritize different elements of research articles than advanced scientists.[18] Novice readers lack the conceptual framework that allows experts, such as faculty, to absorb the new knowledge presented in literature articles and combine it with their existing knowledge. Literature discussion questions provide extra guidance to help students through the parts of the article that they may be most resistant to reading, such as the experimental details and results. Starting with simple questions helps build student confidence and motivation.

Because of the advanced nature of the recent Andersen paper, the authors chose to focus their LO on one aspect of the work, the isomerization of buta-1,2-diene to 2-butyne. A reading guide and thirteen questions were developed and the LO has been published on the VIPEr site.[56] The Andersen LO begins with a simple question on electron configuration and progresses to questions or electron counting in organometallic compounds and reaction mechanism.

A literature discussion learning object does not need to cover an entire article. For example, the Andersen LO focus on limited parts of the introduction, Results and Discussion, and Experimental Section. Faculty may choose to focus on a single section, or even a single paragraph, in a paper. Longer articles can be divided into sections that can then be assigned to small groups of students; this could be followed by a class discussion where each small group takes the lead in presenting the paper.

Because of goals for this particular LO, it is appropriate for a more advanced audience than students completing their first course in inorganic chemistry. Literature discussion LOs are easily developed for lower level students, and many exist on VIPEr. For example, “Bonding in Tetrahedral Tellurate”[58] introduces students to reading experimental protocols / reaction conditions and predicting products and by-products of chemical reactions. “Fivefold Bonding in a Cr(I) Dimer”[59] addresses many topics including the relationship between bond order and structural parameters, drawing MO diagrams, and using character tables. Many of the concepts covered in inorganic chemistry are easily addressed with the primary literature where students can see the concepts in context.

Conclusions

Many inorganic chemists are aware of Richard Andersen’s encyclopedic knowledge of the chemical literature. When asked about a paper, he can typically pull the journal title, author, and publication year out of his head. To fill in the details, he has a mysterious index card system that, in his hands, beats SciFinder any time. For the rest of us, resources like the literature discussions in VIPEr can support teaching inorganic chemistry to our undergraduate and graduate students in the context of the rich, exciting, and compelling research of our field. This approach inspires and motivates students to learn deeply and to engage with the important discoveries of inorganic chemistry.

Conflicts of interest

The authors declare no conflicts of interest.

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Teaching inorganic chemistry using the primary literature motivates students to learn deeply and to engage with the important discoveries of the field.

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