Inorganic Chemistry

Viewpoint

pubs.acs.org/IC

Great Expectations: Using an Analysis of Current Practices To Propose a Framework for the Undergraduate Inorganic Curriculum

Barbara A. Reisner,*[†] Sheila R. Smith,[‡] Joanne L. Stewart,[§] Jeffrey R. Raker,[⊥,¶] Johanna L. Crane,[∥] Sabrina G. Sobel,[#] and Lester L. Pesterfield[$]

[†]Department of Chemistry and Biochemistry, James Madison University, Harrisonburg, Virginia 22807, United States

[‡]Department of Natural Sciences, University of Michigan—Dearborn, Dearborn, Michigan 48128, United States

[§]Department of Chemistry, Hope College, Holland, Michigan 49423, United States

[⊥]Department of Chemistry and [¶]Center for the Improvement of Teaching and Research in Undergraduate STEM Education, University of South Florida, Tampa, Florida 33620, United States

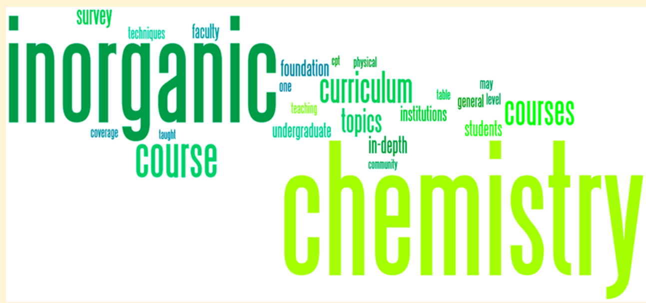
[∥]Department of Chemistry, University of Puget Sound, Tacoma, Washington 98416, United States

[#]Department of Chemistry, Hofstra University, Hempstead, New York 11549, United States

[$]Department of Chemistry, Western Kentucky University, Bowling Green, Kentucky 42101, United States

Ⓢ *Supporting Information*

ABSTRACT: The undergraduate inorganic chemistry curriculum in the United States mirrors the broad diversity of the inorganic research community and poses a challenge for the development of a coherent curriculum that is thorough, rigorous, and engaging. A recent large survey of the inorganic community has provided information about the current organization and content of the inorganic curriculum from an institutional level. The data reveal shared "core" concepts that are broadly taught, with tremendous variation in content coverage beyond these central ideas. The data provide an opportunity for a community-driven discussion about how the American Chemical Society's Committee on Professional Training's vision of a foundation and in-depth course for each of the five subdisciplines maps onto an inorganic chemistry curriculum that is consistent in its coverage of the core inorganic concepts, yet reflects the diversity and creativity of the inorganic community. The goal of this Viewpoint is to present the current state of the diverse undergraduate curriculum and lay a framework for an effective and engaging curriculum that illustrates the essential role inorganic chemistry plays within the chemistry community.



1. INTRODUCTION

"There is no single course in inorganic chemistry."

This statement resonates with many of us who teach inorganic chemistry. Ask 10 organic chemists what is covered in week four of Organic Chemistry II, and it is likely that you will get a similar response across a wide range of institutional types. Ask 10 inorganic chemists the analogous question about their advanced inorganic chemistry course, and it is likely that you will get 10 different responses including "we only offer one semester". This presents inorganic chemists with a unique challenge in developing, teaching, and assessing our courses. Conversely, it gives us tremendous freedom and flexibility in what and how we teach.

When we teach a course in inorganic chemistry, we are charged with introducing our students to a field covering a wide range of elements, molecules, materials, and reactivities. The unusual flexibility of the undergraduate inorganic chemistry curriculum[1] and a mandate of only a single semester by the American Chemical Society's Committee on Professional Training (ACS CPT)[2] have led to great diversity in how inorganic chemistry is taught.[3,4] Institutions report splitting inorganic chemistry into one, two, or even three courses with a wide range of prerequisites. Some institutions weave inorganic chemistry topics into other courses in the curriculum. In fact, the way inorganic chemistry is taught is a result of personal and institutional history as much as any other factor. We teach what we know and find interesting because CPT and our institutions provide us with the flexibility to make such choices.

There has not been a broad survey of the inorganic chemistry curriculum since 2001.[5] A subset of the 2014 Inorganic Chemistry ACS Exam Committee wanted to better understand the undergraduate curriculum to help with the development of a new foundation-level inorganic chemistry exam for the ACS Examinations Institute. This survey, completed in Fall 2013 in cooperation with the ACS Division of Inorganic Chemistry

Received: June 11, 2015
Published: August 31, 2015

ACS Publications © 2015 American Chemical Society

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

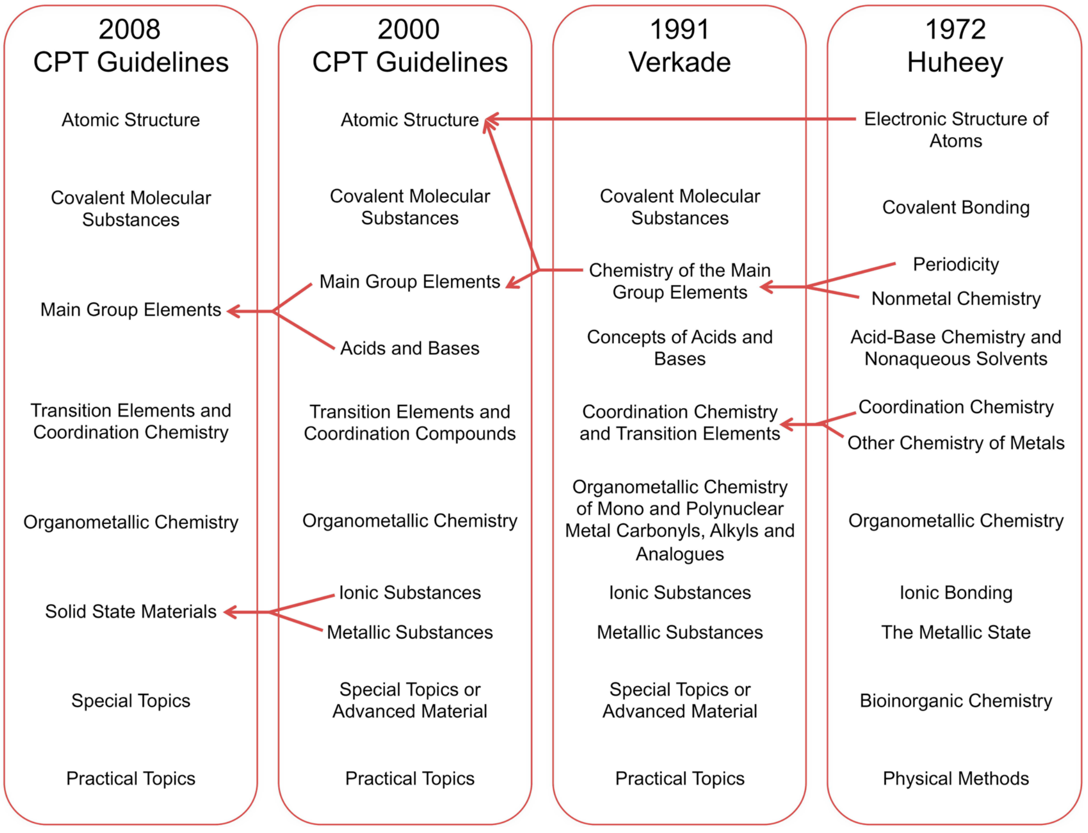


Figure 1. Origin and evolution of the organized inorganic chemistry curriculum.[1,33,34]

(DIC) and Interactive Online Network of Inorganic Chemists (IONiC), provides enlightening, informative, and possibly even formative insights into the undergraduate inorganic curriculum.

A broad population of potential respondents was possible through the cooperation of DIC and IONiC, and we invite continued broad participation through the publication of this Viewpoint. The description of the survey results, in addition to prior analysis,[3,4] are especially valuable to new faculty who wish to understand how inorganic chemistry is taught, faculty who seek to strengthen the inorganic chemistry offerings in their department, the ACS Examinations Institute Committees who develop exams in the field, and faculty who want a more complete snapshot of the preparation of incoming graduate students.

Most importantly, we hope the results will prompt a discussion, inclusive of a wide range of faculty involved in both undergraduate and graduate inorganic chemistry education, on the critical elements of undergraduate inorganic chemistry. We have a unique opportunity to consider these data as a community in order to build the framework for teaching inorganic chemistry in the 21st century. We begin with a brief history of the inorganic curriculum in order to emphasize the importance of community advocacy in this process.

2. A BRIEF HISTORY OF TIME: THE CHANGING INORGANIC CURRICULUM

In the 19th and early 20th centuries, inorganic and general chemistry were used synonymously to describe the first-year college-level curriculum. It was not until the middle of the 20th century that inorganic chemistry came to be regarded as a discipline with its own identity.[6] "Inorganic" chemistry textbooks of the early days (for example, Newell 1909[7]) included what we would recognize today as an introduction to the science of chemistry and chapters on the qualitative chemistry of the elements. This course was taught as a collection of facts without an underlying theoretical framework except for a loose association with periodic trends.[8] As new physical methods and theoretical techniques developed in the 20th century, the introductory chemistry course became more focused on physical chemistry.[8−15] The emergence of inorganic chemistry as a core subdiscipline in chemistry and the slow transition of the inorganic class from "general chemistry" to an independent course help to explain the diversity in the current inorganic curriculum. This progression can be followed through Labinger's recent history of the field,[6] reports from the *Journal of Chemical Education* (*JCE*), and the recommendations provided by the CPT for program certification.[16] Taken together, these sources provide insights on the development of the inorganic course(s) in the United States.

The original CPT guidelines from 1939 required a course in general chemistry but contained no formal requirement for a course in inorganic chemistry. It was assumed that general chemistry would provide instruction in basic inorganic chemistry, which at the time consisted of descriptive chemistry and qualitative analysis.[16] Recognizing that the general course had evolved and inorganic chemistry had advanced as a field, the inorganic chemistry community began a concerted effort to advocate for a separate and additional course in inorganic chemistry.[9,17−20] A symposium titled "The Place of Inorganic Chemistry in the Undergraduate Curriculum" was held at the 116th meeting of the ACS in 1949, and reflections on the nature of these proposed courses and current practices at individual institutions were published in *JCE*.[12,21−23] Even at this point, it is clear that there was little standardization in the curriculum; institutions developed curricula that met their local needs.

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

Remarkable changes in chemistry between the end of World War II and the 1970s affected the presence of inorganic chemistry in the general chemistry course. Through the 1950s, a great deal of qualitative analysis and aqueous inorganic chemistry were taught in the general chemistry laboratory. As safety and industrial hygiene grew in importance in the 1960s and 1970s, qualitative analysis laboratories began to disappear from the curriculum, making the descriptive chemistry portion of the lecture less relevant as prerequisite knowledge for other courses. Coupled with a revolution in physical and theoretical methods, qualitative analysis was replaced by more physical chemistry oriented topics in the introductory lecture. General chemistry textbooks began to reflect these changes too, despite the many discussions that descriptive chemistry should be brought back.[24−29]

The 1950s also marked the evolution of inorganic chemistry to a field with its own identity, specialized conferences, and journals in the US.[6] In 1957, the Division of Physical and Inorganic Chemistry split into the Division of Inorganic Chemistry and the Division of Physical Chemistry.[30,31] In 1961, the ACS Exams Institute chaired by S. Young Tyree, Jr. released its first inorganic chemistry exam.[32] While the written record of this era is incomplete, one can postulate that the 1962 CPT requirement for a semester of inorganic chemistry, in addition to the basic inorganic chemistry covered in the introductory chemistry course, was a result of the vigorous lobbying from the inorganic chemistry community.

The Inorganic Subcommittee of the Curriculum Committee of the ACS proposed an outline for the undergraduate inorganic chemistry curriculum in 1972.[33] These suggestions are compared to more recent recommendations in Figure 1. This group recommended that inorganic chemistry be taught after a semester of physical chemistry and some organic chemistry. Huheey's influence on this subcommittee was apparent because he authored a well-known undergraduate inorganic chemistry textbook that paralleled the recommendations of the inorganic subcommittee.

Although the intent was to strengthen the inorganic chemistry curriculum,[16] the 1977 revision of the CPT guidelines was seen as a step backward. According to the CPT guidelines, "The [basic] inorganic chemistry should include descriptive chemistry dealing in a systematic way with the elements and the structures, properties and reactions of their compounds." If programs do not include this chemistry in the introductory coursework, "the systematic chemistry of the elements should be given strong emphasis in a required "advanced" inorganic course". This language implied that general chemistry could include basic inorganic chemistry to give programs greater flexibility in meeting the new recommendations; however, equating inorganic chemistry and general chemistry once again was seen as a setback.[34] These revised guidelines led to another effort by the community to upgrade the status of inorganic chemistry, with a symposium at the 1980 National Meeting in Las Vegas titled "Inorganic Chemistry in the Curriculum: What should be left in and what should be left out".[26,35−42]

The place of inorganic chemistry in the curriculum was strengthened with the 1983 revision of the CPT guidelines, which required parity among organic, analytical, physical, and inorganic chemistry in the lecture sequence. A one-semester post-general chemistry course in inorganic chemistry and an upper level course with organic and physical chemistry prerequisites were required. The 1988 extension of the CPT guidelines further refined the recommended inorganic curriculum. In these guidelines, two semesters of inorganic chemistry were required, but one semester could be an elementary (first-year) course and the other course could be an intermediate course without a physical chemistry prerequisite. This recommendation, which allowed departments to move inorganic chemistry earlier in the curriculum, led again to the formation of an Ad Hoc Subcommittee of the ACS Division of Inorganic Chemistry to suggest topics for the intermediate inorganic course for universities electing to adopt the new guidelines.[34] In 2008, the guidelines were revised to introduce the idea of foundation and in-depth courses. Analytical, biochemistry, inorganic, organic, and physical chemistry would all have a required foundation course with general chemistry as the prerequisite. In addition, four in-depth courses that have one or more foundation courses as prerequisites would be required. The recommendations of topics for inclusion in inorganic chemistry in the 2008 guidelines can be found in Figure 1. More detailed topical outlines can be found in the original sources.[1,33,34] The 2015 CPT guidelines leave the requirement for four in-depth courses intact[2] but add a specific requirement for coverage of larger-scale systems such as polymers.[43] This recommendation could encroach on inorganic chemistry if departments add another course to the curriculum that students can take instead of in-depth inorganic. This returns us to the problem that was described earlier: some departments still believe that only one semester of inorganic chemistry is necessary because of the misconception that general chemistry is inorganic chemistry. Driven by curiosity about how these changes might affect inorganic chemistry and recognizing that over a decade had passed since the last similar community survey, the authors investigated the current state of inorganic chemistry in the undergraduate curriculum.

3. HOW THINGS WORK: SURVEY AND METHODOLOGY

A subset of members of the 2014 Inorganic Chemistry ACS Exam Committee developed the new survey to guide current and future Exam Committees in revisions to the existing exam and for the development of a new exam. The survey was designed to capture topics that might be covered in both foundation and in-depth courses. Survey items were developed based on the 2008 ACS CPT guidelines, two articles published in *JCE*,[5,44] and previous Inorganic Chemistry ACS Exams. Detailed discussions of survey population and results have been published previously[3,4] and can also be found in the Supporting Information.

4. AS YOU LIKE IT: WHERE AND WHEN IS INORGANIC CHEMISTRY OFFERED?

Inorganic chemistry continues to be an integral part of the undergraduate curriculum. Most respondents (Table S1) require at least one course in inorganic chemistry beyond general chemistry. It is somewhat surprising that fewer than 100% of ACS-approved departments require one course in inorganic chemistry because a foundation course in inorganic chemistry is a CPT requirement. It could be that this number provides insights on reporting errors or it could be that these are institutions that have parsed their inorganic curriculum out to other courses. There are no differences among bachelor's, master's, and doctoral level institutions. It is clear from the data that most graduates of a chemistry program have some exposure to the basic principles of inorganic chemistry.

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

However, there is significant variability in *how many* inorganic chemistry courses are offered and *when* institutions offer those courses (Tables S2 and S3). The survey found that 31% of responding institutions offer a single course, 49% offer two, and 20% offer three or more courses. Graduate institutions offer a greater number of in-depth and advanced courses relative to bachelor's institutions, which possibly reflects differences in the number and type of inorganic faculty present at an institution and the contribution of graduate students to enrollment.

Since the 2001 survey, there has been some shift in the placement of the first course in inorganic chemistry from the junior/senior level to the first/second year level, although inorganic chemistry is still primarily taught as a junior/senior level course (Table S4). There is significant variability in the prerequisites for the foundation level and in-depth courses (Tables S5 and S6).

The diversity in inorganic chemistry offerings, as reported in the survey data, reflects the lack of standardization in the field relative to courses such as general, organic, and physical chemistry, which typically have a sequence of two courses each. This diversity highlights the importance of community advocacy in developing a shared vision of undergraduate education for the 21st century and the importance of discussing coverage at the department level to make sure that critical concepts are not overlooked.

5. A TALE OF SEVEN COURSES

Cluster analysis was used to reveal patterns in the topics faculty cover in their inorganic courses. Detailed descriptions of the results can be found in the *JCE* papers,[3,4] but a brief summary will be provided here. Four distinct foundation inorganic chemistry courses with unique topical profiles were identified. Two of them are best described as survey courses: one emphasizes a smaller number of fundamental topics and the other covers "everything plus the kitchen sink". The other two foundation courses that emerged differ most markedly in their coverage of descriptive chemistry. The one that includes descriptive chemistry emphasizes atoms, bonding, and main-group chemistry. The course that excludes descriptive chemistry emphasizes transition-metal chemistry, with topics such as coordination chemistry, organometallic chemistry, bioinorganic chemistry, and materials.

Cluster analysis of the in-depth course content revealed three distinct course types. Similar to the foundation courses, two of the in-depth courses can best be described as survey courses with different amounts of coverage. The third cluster includes narrower special topics courses. The data did not indicate any links between specific foundation course types and in-depth course types. We cannot speculate on how institutions view the connection between their foundation and in-depth courses because no trends emerged. This disconnect might be a symptom of the lack of a clear shared vision for what an effective inorganic curriculum should look like or reflect the differences in offerings at the institution level.

A key finding is that some core topics are nearly always covered whether an institution has one or several courses (the italicized topics in Table 1). Table S7 presents how coverage of these topics has changed in the past 5 years showing that bioinorganic chemistry, materials chemistry and nanoscience, and organometallic chemistry are increasingly included in the undergraduate curriculum. While some members of the community may recognize a satisfying parallel between the core topics and the syllabus of their foundation course, more would probably be concerned with the topics that are missing. All chemistry

Table 1. Percentage of Respondents Covering Each Topic in Foundation and In-Depth Inorganic Chemistry Courses[a]

topic	foundation level (n = 317)	in-depth level (n = 185)
atoms and electronic structure	96	63
covalent bonding and molecular orbital theory	94	84
transition-metal complexes and coordination chemistry	90	91
acids, bases, and solvents	77	48
symmetry and group theory	75	84
solids and solid-state chemistry	75	50
redox chemistry	62	46
main-group and descriptive chemistry	55	34
organometallic chemistry	45	84
bioinorganic chemistry	33	54
materials chemistry and nanoscience	22	33
analytical techniques	18	29
nuclear chemistry	17	8
green chemistry	3	8

[a]Core topics that are almost always covered in the foundation course are highlighted in italics.

instructors have struggled with the problem of coverage. Despite consistent evidence that "less is more" with respect to student learning,[45,46] the survey data suggest that many of us still try to squeeze everything into our allotted courses.

6. THE JOY OF COOKING: THE INORGANIC CHEMISTRY LABORATORY

Respondents were asked specifically if their institution "requires that chemistry majors take one or more semesters of inorganic chemistry laboratory". Approximately 80% of all institutions require inorganic chemistry laboratory for all undergraduates, although 13% of institutions integrate inorganic laboratory with other subdisciplines (Tables S8 and S9). The survey results indicate no dependence on the institution type, but a difference is seen between ACS- and non-ACS-approved programs with approximately one-third of non-ACS programs not requiring laboratory.

Respondents who have taught a laboratory course in the last 5 years were asked about the characterization methods used in their inorganic laboratory course. Spectroscopic techniques are the dominant means of characterization in laboratory courses. The most common techniques are IR (96%), UV−visible (95%), and NMR (84%) spectroscopies. Magnetic susceptibility (72%) is also a relatively common technique (Figure 2). A full list of techniques covered in the laboratory and lecture courses can be found in the Supporting Information (Figure S1 and Table S10).

There has been modest growth of the use of computational chemistry in the laboratory curriculum since the last survey. In 2001, 30% of laboratory programs reported doing some computational work. This has increased to 40% of programs in 2013. As this technique becomes more important in the inorganic chemists' toolbox, additional instruction at the undergraduate level may be appropriate.

The smaller percentages reported for other techniques may reflect the lack of instrumentation available at some institutions. The tools used to characterize extended systems are generally poorly represented. Because extended systems have critical roles in the chemical industry, instruction on the synthesis, analysis, and characterization of these materials should be considered. The

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

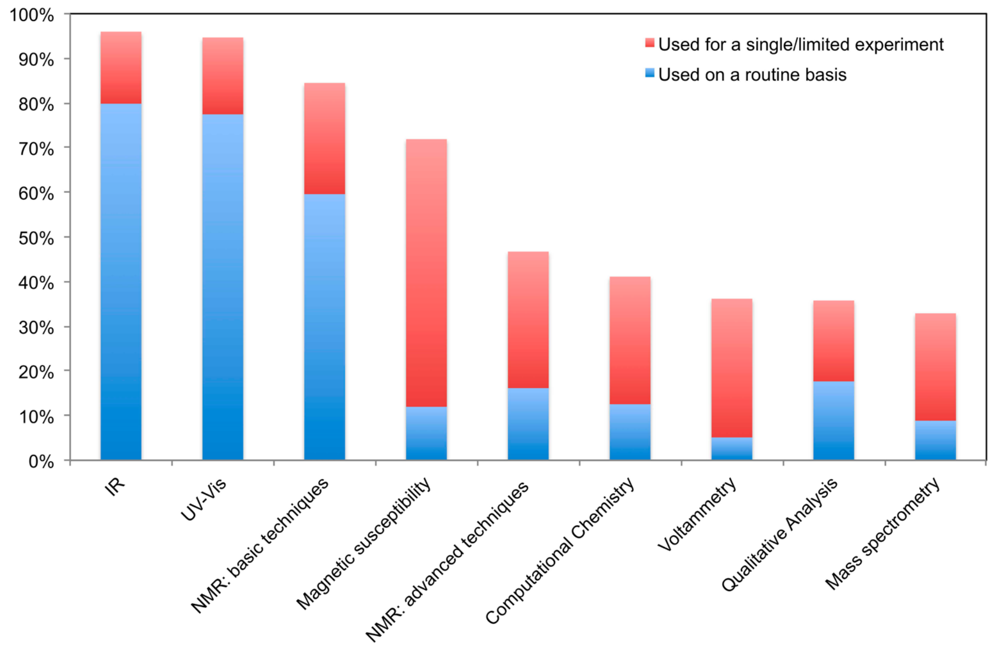


Figure 2. Techniques most commonly used in the inorganic chemistry teaching laboratory.

absence of these techniques may reflect either a lack of access to characterization tools or little faculty experience.

Synthetic techniques were not addressed in the current survey. However, synthesis using inert-atmosphere techniques was among the most common write-in responses in the survey, indicating a significant interest and investment in teaching these techniques.

We were surprised at how few respondents reported teaching analytical techniques in the lecture course because techniques like magnetic susceptibility and spectroscopy are covered in most inorganic chemistry texts. It is possible that faculty who mention these techniques with limited detail did not feel that they covered analytical techniques but rather theory in lecture and therefore did not report covering analytical techniques.

7. THE COURAGE TO TEACH: INSTRUCTIONAL TECHNIQUES AND RESOURCES FOR TEACHING INORGANIC CHEMISTRY

Since the 2001 survey, nonlecture methods of teaching have become more widely used, an unsurprising result because projects like the Multi-Initiative Dissemination Project Workshops[47] have promoted awareness of techniques like Process Oriented Guided Inquiry Learning (POGIL),[48] Peer-Led Team Learning (PLTL),[49] case-based teaching,[50] and problem-based learning. Lecture still dominates instructional methods, but a majority of classes now involve some sort of in-class activities (Table S11). Only 1 in 10 courses at primarily undergraduate institutions and 1 in 3 courses at graduate institutions are lecture-only courses. The most obvious hypothesis for this divergence is a difference in the class size, with smaller classes lending themselves better toward active learning, but an analysis of the teaching method as a function of the institution type and class size reveals that the institution type, and not the class size, is the dominant factor in whether a course will be lecture-only (Table S12). At this time, only a handful of institutions reported teaching an inorganic chemistry course using the flipped classroom model, and none reported offering a distance learning course.

Another change since 2001 is the number of new resources and instructional technologies that have become available to teach inorganic chemistry (Table S13). In 2001, 67% of respondents reported never using the Internet and only 2% used this resource often. Now 69% of respondents use some sort of online resource in teaching inorganic chemistry. The textbook still plays an important part in the inorganic course with 97% of respondents still using this resource. Faculty from bachelor's institutions are just as likely as faculty at graduate institutions to use articles from the primary literature in their class and are more likely to incorporate activities from *JCE*. While they are equally likely as their colleagues at graduate institutions to use a resource like Wikipedia, BA/BS faculty are more likely to use an online resource like the Virtual Inorganic Pedagogical Electronic Resource (VIPEr)[51] or the National Science Digital Library (NSDL).[52] These resources provide not only a repository of activities but also a forum for the discussion of teaching inorganic chemistry.

Fewer than 1 in 10 institutions are using online homework for inorganic chemistry. Commercially available online homework in inorganic chemistry is a relatively new phenomenon, and the question banks have not been fully developed because of the relatively small market. It will be interesting to see if adoption of this resource increases as the materials and market mature.

A number of faculty reported using other resources to teach inorganic chemistry.[53] Examples include general interest articles, textbook resources, model kits, self-recorded lectures, Web sites,[54] modeling or structural software, search tools, computational software, specialized features of learning management systems, Institute of Chemical Education resources, and online databases. The ready availability of these and other resources creates a large toolkit from which an inorganic instructor can choose.

8. GREAT EXPECTATIONS

The diversity in the undergraduate curriculum has many implications. Without a clear and agreed upon set of expectations for our students, the breadth and depth of student learning will

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

Table 2. Topics and Themes That Represent the Common Elements of Courses Taught in the Inorganic Curriculum

core topics for the foundation course	core topics to further develop in an in-depth course	advanced topics or themes for an in-depth course
atoms and electronic structure (including periodicity)	atoms and electronic structure (including periodicity)	bioinorganic chemistry
symmetry and group theory	symmetry and group theory	organometallic chemistry
covalent bonding models and molecular orbital theory	covalent bonding models and molecular orbital theory	materials chemistry and nanoscience
solids and solid-state chemistry	solids and solid-state chemistry	analytical techniques (taught in the lecture course)
acids, bases, and solvents	transition-metal complexes and coordination chemistry	
redox chemistry		
transition-metal complexes and coordination chemistry		
main-group and descriptive chemistry		

Common concepts taught in each of these topics are included in the Supporting Information (Tables S16−S27 and associated discussion).

depend not only on the level of academic engagement of the student but also on the institution. This affects the design of standardized assessments, the preparation of students for graduate school or the workforce, and even the careers to which our students aspire.

Respondents were asked to differentiate the relative importance of topics for entering graduate students into Critical Knowledge (content knowledge an entering graduate student should know), Important Knowledge (content knowledge an entering graduate student should be familiar with), and Not Critical. Faculty expect students to be familiar with an impressive amount of material (Table S14). In many cases, faculty expect students to know far more than what is covered in most inorganic classes. For example, while 97% of faculty say that it is critical or important that students be familiar with redox chemistry, only 62% report teaching this topic at the foundation level and 46% at the in-depth level (Table S15). It is interesting to note that faculty at undergraduate institutions place more topics in the Critical Knowledge and Important Knowledge categories than graduate faculty (Table S14). The reasons for these differences are not clear. One speculation is that a graduate faculty may simply recognize the variability of the preparation of undergraduates coming from many different programs. Although not surprising to the authors, solids were deemed as critical to only 21% of respondents. While much of inorganic chemistry has a small-molecule focus, the understanding of solids and intermolecular forces is critical to many inorganic applications. This material should not be neglected in the inorganic curriculum and should be considered critical knowledge in the field.

These disparities confirm that we need to examine the inorganic curriculum carefully to make sure that the expected materials and critical concepts are being covered somewhere in the undergraduate curriculum. The CPT plays a role in this by codifying the number of courses that institutions should offer and suggesting the material that courses should cover. Ultimately, the vibrant and dynamic diversity of the field makes a prescriptive mandate difficult to design and impossible to enforce. A single mandated curriculum for inorganic chemistry is unlikely to succeed in any case and would meet resistance not only from our colleagues in inorganic chemistry but also from other disciplines as we encroach upon territory that they view as their own; nevertheless, the data from this survey can certainly suggest a framework for a curriculum that could serve as a starting point for the development of foundation and in-depth courses.

9. A MODEST PROPOSAL

So how should we respond to these data? What are the critical learning outcomes for a first course in inorganic chemistry? What concepts need to be covered in more depth, benefiting from an early introduction in the curriculum, followed by deeper treatment in a more advanced course? What misconceptions and outdated models persist that need to be updated or eliminated? What constitutes an *effective and engaging* inorganic chemistry curriculum that promotes in-depth learning and encourages students to continue study in inorganic chemistry?

This survey indicates that the community already has a shared vision of topics that are essential to the study of inorganic chemistry (Table 2). These topics would appear, ideally, in a first or foundation course in inorganic chemistry. We are not saying that these are the *only* topics that should be covered but believe that a well-structured foundation course that does not try to do too much is the most effective way to begin the inorganic curriculum. Research on student learning has shown that the *drinking from a firehose* approach leads to surface rather than deep learning or good retention,[45,46] and current efforts in science education reform are focusing on smaller numbers of "disciplinary core ideas",[55] "anchoring concepts",[56] and "learning progressions".[57,58]

Most of these core topics appear again in more than half of current in-depth courses (Table 2), allowing for deeper coverage. For example, if the in-depth course is taken after students have completed physical chemistry, the basic ideas about atomic structure can be connected more closely to quantum mechanics. The chemistry of coordination compounds can be extended to cover spectroscopy. Symmetry concepts can be expanded to include more advanced ideas in group theory and the molecular orbital treatment of more complex molecules. This is not unlike the three-tiered approach to the inorganic curriculum that was discussed during the 1980 symposium. The tiers are not intended to repeat concepts but rather to build upon concepts as the student's level of chemical sophistication grows.[41,42]

The survey also suggests several topics that are best reserved for more advanced study (Table 2) in an in-depth course or in special topics courses. Organometallic, bioinorganic, and materials chemistry are all well-established research areas, yet only organometallic chemistry enjoys regular inclusion in the inorganic curriculum. This may be partly textbook-driven. In undergraduate textbooks, advanced topics fall at the end of the book and are often given only cursory coverage or left out completely. In the hands of an instructor who has little personal experience in a subdiscipline like bioinorganic or materials chemistry, weak textbook coverage may lead to the omission of these more advanced topics. Fortunately, online teaching resources can help instructors with little experience teach these topics in engaging ways. For example, VIPEr has a short introduction to bioinorganic chemistry that helps students understand why biology employs metals in many roles, given their limited bioavailability and frequent toxicity.[59] In materials chemistry, there are many resources to help students understand

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

and visualize the structures of extended systems.[60−63] These materials can provide exciting new applications of fundamental topics.

A two-semester model for inorganic chemistry, similar to that devoted to physical and organic chemistry in many curricula, can facilitate the development of an effective inorganic chemistry curriculum. The first semester, with no physical chemistry prerequisite, could cover the core topics in Table 2, preferably with the introduction of examples that touch on the areas of solid-state materials, bioinorganic, and organometallic chemistry. A second-semester course, preferably with a physical chemistry pre- or corequisite, could take many forms but would build on the basic foundation laid in the first-semester course to further develop the core topics listed in column 2 of Table 2 and include some coverage of research topics in column 3 of Table 2.

A tiered model of coverage also provides opportunities to integrate ideas across chemistry and to identify the best models to explain chemical phenomena. For example, structure and bonding are first introduced in general chemistry, where students learn Lewis theory so that they can predict the shape of a molecule using VSEPR. Organic chemists emphasize valence bond theory, and physical chemistry uses quantum approaches. Inorganic chemistry is likely the first class where students have a chance to step back and see how chemists use *multiple models* to explain chemical phenomena. Learning how and when to use different models[64,65] may well be the biggest challenge of learning chemistry, particularly inorganic chemistry. To complicate things, some of the inorganic chemistry that remains in the standard general chemistry sequence is arguably *incorrect*, for example, the use of d-orbital hybridization to explain exceptions to the octet rule.[66] In our courses, we can help students move beyond learning chemistry as isolated topics and move toward a more integrated understanding of complex ideas and underlying chemical concepts.[57,58]

A scaffolded, two-semester approach that avoids covering too much has the potential to be an *effective* curriculum, but to develop student interest, it must also be an *engaging* curriculum. Incorporating exciting and current examples from the literature[67,68] in both foundation and in-depth courses can increase student interest and help students develop their understanding of how chemists use models in different contexts. Seeing the relevance and applications of inorganic chemistry will whet the appetite of an undergraduate to *choose* to pursue an in-depth course of study in inorganic chemistry where one exists or spark a passion for study when the opportunity next presents itself. Incorporating current literature into the classroom is a challenge because textbooks cannot easily keep up with the latest developments in chemistry and chemists cannot possibly read all of the literature in all of the subdisciplines of inorganic chemistry. Online resources that encourage the development and exchange of materials based on the current literature make it possible to easily update a course with timely content. Examples can be found that tie some of the simplest concepts, such as Lewis dot structures,[69] to exciting new compounds[70] or that ask students to grapple with the relationship between Lewis structures and bonding models.[71] Other materials focused on the primary literature can tie research at the frontiers of inorganic chemistry to basic chemical concepts such as using physical methods to understand the characterization of metalloenzymes[72] or tuning the band gap in thin-film solar cells.[73]

Courses can also be made more engaging by increasing the use of practices that have been shown to be more effective than lecture, most of which can be used in large or small classes. These practices include collaborative learning, peer instruction, in-class activities, interactive simulations,[74] case studies,[50] and problem-based learning.[75−77] While a majority of respondents are incorporating in-class activities into their instruction, we should ask ourselves whether these instructional practices mirror the ways of thinking that we practice in research. Are we engaging students with questions the same way that we do in the research laboratory? We all highlight chemical literature, but how frequently do we do literature-based discussion? Both our students and the field will benefit from engaging in authentic scientific practices in the classroom. By using these strategies and incorporating techniques from the learning sciences into the classroom,[78] we can help students develop a robust understanding of inorganic chemistry.

10. A BRAVE NEW WORLD

The inorganic community has come together many times to discuss the state of the undergraduate inorganic chemistry curriculum. On a basic level, our courses affect the preparation of our students. More broadly, they affect how we inspire students and provide them with the tools to push the boundaries of inorganic chemistry and solve the scientific and technological challenges we face. The results from this survey begin to answer the question of *what* we are doing so that we can begin to answer the question, what *should* we be doing?

There is no single course in inorganic chemistry, but there should be elements of inorganic chemistry with which all of our students are familiar. Our students should connect fundamental concepts to the primary literature and develop the skills they need to work at the frontiers of inorganic chemistry. As a community, we need to establish what is essential for the undergraduate inorganic curriculum and advocate for strong coverage of inorganic chemistry. We need to engage in a discussion of our teaching and share pedagogical content knowledge such as common misconceptions to improve the education of the next generation of inorganic chemists.

To begin this conversation, IONiC has created a Forum Topic on VIPEr[79] to encourage a discussion of the survey results, to identify important topics that we may have missed, and to share strategies to ensure inorganic chemistry has a robust position in the curriculum. The DIC has sponsored a session on Undergraduate Teaching at the Frontiers of Inorganic Chemistry to be held at the 251st ACS National Meeting in March 2016, and we encourage members of the inorganic chemistry community to participate. We invite you to continue this conversation and shape the future of inorganic chemistry.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.inorgchem.5b01320.

Acronyms used in this manuscript and supporting data (PDF)

Additional analysis of topics taught in the inorganic curriculum (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: reisneba@jmu.edu.

Notes

The authors declare no competing financial interest.

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

Biographies

Barbara A. Reisner earned her A.B. (1993) in Chemistry from Princeton University and her Ph.D. (1998) from the University of California, Berkeley, with Professor Angelica M. Stacy. She completed her postdoctoral training under the joint supervision of Professor John B. Parise at Stony Brook University and Dr. Brian H. Toby at the National Institute of Standards and Technology. She is a Professor of Chemistry at James Madison University, where she investigates the synthesis and characterization of inorganic−organic framework materials with undergraduates. Professor Reisner has worked in several positions with the ACS Division of Inorganic Chemistry and has recently chaired the Inorganic Chemistry (2014) and Foundations of Inorganic Chemistry (2016) exam committees for the ACS Exams Institute. She is a member of the Leadership Council of IONiC (Interactive Online Network of Inorganic Chemists).

Sheila R. Smith earned her B.S. (1992) in Chemistry from North Carolina State University and her Ph.D. in Inorganic Chemistry (Bioinorganic) in the laboratory of H. Holden Thorp at The University of North Carolina (1997). After postdoctoral studies with Joan B. Broderick (Amherst College and Michigan State University) and John L. McCracken (Michigan State University), she joined the faculty of the University of Michigan—Dearborn in 2001. Her research interests include copper transport and storage in oviparous species, and NO_x reduction by copper and iron complexes. Professor Smith is a member of the Leadership Council of IONiC, has served on several ACS Exam Committees (Inorganic, DUCK), and is currently a member of the ACS DIC Council (Alternate Councilor).

Joanne L. Stewart received her B.A. (1982) in Chemistry from Kalamazoo College. As an undergraduate, she did research with Professor Thomas Smith and Professor Malcolm H. Chisholm. She earned her Ph.D. (1988) from the University of California, Berkeley, with Professor Richard A. Andersen. She is currently Professor of Chemistry at Hope College. Her professional interests are in the scholarship of teaching and learning and in studying the impact of communities of practice such as IONiC on faculty development. Professor Stewart was a Carnegie Scholar (2005) with the Carnegie Academy for the Scholarship of Teaching and Learning program (CASTL) and has served as director of Hope College's Howard Hughes Medical Institute program.

Jeffrey R. Raker received his B.S. (2003) in Chemistry from Ohio Northern University and his M.A. (2005) in College Student Personnel from Bowling Green State University. Raker received his Ph.D. (2011) in Chemical Education from Purdue University, supervised by Professor Marcy H. Towns. After postdoctoral research supervised by Professor Thomas A. Holme at Iowa State University and the ACS Examinations Institute, Dr. Raker joined the Chemistry Department at the University of South Florida. Professor Raker studies learning in organic chemistry and across the chemistry curriculum via qualitative and survey research methodologies. He is Associate Director of the ACS Examinations Institute, a member of IONiC, and a founding member of the Center for the Improvement of Teaching & Research in Undergraduate STEM Education (CITRUS) at the University of South Florida.

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868

Johanna (Jo) Crane is a Professor of Chemistry at the University of Puget Sound in Tacoma, WA. She studied chemistry and education at Muskingum College (B.S., 1989) and received her Ph.D. (1994) from Washington University in St. Louis, MO, under the direction of Professor William E. Buhro. She began teaching general and inorganic chemistry at Alfred University before moving to Puget Sound in 1999. Professor Crane's research with undergraduates involves the synthesis and characterization of coordination polymers, metal–organic frameworks, and metallogelators. She is also engaged in laboratory development that integrates materials science into the general and inorganic chemistry curriculum.

Sabrina Sobel earned her B.A. (1987) in Chemistry from Pomona College and was awarded the Rowan Memorial Award for being "the student who shows the best promise of making the most contributions to Chemistry". She earned her Ph.D. in Inorganic Chemistry from University of California, Berkeley (1993), where she completed her thesis work partially under Professor W. Armstrong and as a guest researcher in Dr. E. Stiefel's group at IBM Almaden Research Center. Professor Sobel has spent her career at Hofstra University as the sole inorganic chemist in the department. She has mentored both undergraduates and high school students in research and now serves as the Chair of the department of Chemistry at Hofstra. Her research is an eclectic mix of the study of biologically relevant zinc compounds, oscillating chemical reactions, and aluminum corrosion. Professor Sobel has served on three rounds of the development of ACS standard undergraduate inorganic chemistry exams and is now serving on the ACS DUCK Exam Committee.

Lester L. Pesterfield received his B.A. (1985) and Ph.D. (1991) from the University of Tennessee under the supervision of Dr. G. K. Schweitzer. He is currently a professor of inorganic chemistry and codirector of the SKyTeach program at Western Kentucky University. Professor Pesterfield's research interests lie in lanthanide coordination chemistry and the development of pedagogical methods for all levels of chemistry.

■ ACKNOWLEDGMENTS

We thank the inorganic chemistry faculty members who gave their time to complete the survey, the leadership of the ACS DIC and IONiC for providing the research team with contact information for the survey participants, and the CPT for providing historical documents. We also thank the members of the 2014 Inorganic Chemistry and 2016 Foundations of Inorganic Chemistry ACS Exam Committees for their work with identifying learning outcomes for an inorganic curriculum. We appreciate the comments that J. W. Gilje, L. Boisvert, and the members of the Leadership Council of IONiC provided during the preparation of this manuscript. This work was supported by NSF Grant DUE-1225792.

■ REFERENCES

(1) Committee on Professional Training Inorganic Chemistry Supplement. https://www.acs.org/content/dam/acsorg/about/governance/committees/training/acsapproved/degreeprogram/inorganic-chemistry-supplement.pdf (accessed June 1, 2015).
(2) Committee on Professional Training. *Undergraduate Professional Education in Chemistry*; American Chemical Society: Washington, DC, 2015.
(3) Raker, J. R.; Reisner, B. A.; Smith, S. R.; Stewart, J. L.; Crane, J. L.; Pesterfield, L.; Sobel, S. G. *J. Chem. Educ.* **2015**, *92*, 973–979.
(4) Raker, J. R.; Reisner, B. A.; Smith, S. R.; Stewart, J. L.; Crane, J. L.; Pesterfield, L.; Sobel, S. G. *J. Chem. Educ.* **2015**, *92*, 980–985.
(5) Pesterfield, L. L.; Henrickson, C. H. *J. Chem. Educ.* **2001**, *78*, 677–679.
(6) Labinger, J. A. Up from Generality: How Inorganic Chemistry Finally Became a Respectable Field. In *SpringerBriefs in Molecular Science*; Rasmussen, S. C., Ed.; Springer: Heidelberg, Germany, 2013.
(7) Newell, L. C. *A Course in Inorganic Chemistry for Colleges*; D. C. Heath: Boston, MA, 1909.
(8) Nyholm, R. *J. Chem. Educ.* **1957**, *34*, 166–169.
(9) Coles, J. S.; Clapp, L. B.; Epple, R. P. *J. Chem. Educ.* **1949**, *26*, 10–14.
(10) Hered, W. *J. Chem. Educ.* **1941**, *18*, 439–440.
(11) Friedenberg, E. Z. *J. Chem. Educ.* **1944**, *21*, 41–44.
(12) Tyree, S. Y., Jr. *J. Chem. Educ.* **1950**, *27*, 447–448.
(13) Audrieth, L. F. *J. Chem. Educ.* **1950**, *27*, 453–457.
(14) Schumb, W. C. *J. Chem. Educ.* **1951**, *28*, 297–299.
(15) Latimer, W. M. *J. Chem. Educ.* **1950**, 27, 451–453.

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859–8868

(16) American Chemical Society Committee on Professional Training. *A retrospective on the ACS-CPT Guidelines 1936−1992*; CPT Newsletter; ACS CPT: Washington, DC, 1992.
(17) Selwood, P. W. *J. Chem. Educ.* **1941**, *18*, 414−417.
(18) Rochow, E. G. *J. Chem. Educ.* **1947**, *24*, 490.
(19) Tyree, S. Y., Jr.; Knight, S. B. *J. Chem. Educ.* **1949**, *26*, 307−309.
(20) Sisler, H. H. *J. Chem. Educ.* **1953**, *30*, 551−553.
(21) Brown, H. C.; Rulfs, C. L. *J. Chem. Educ.* **1950**, *27*, 437−440.
(22) Fernelius, W. C. *J. Chem. Educ.* **1950**, *27*, 441−443.
(23) Wilkinson, J. A. *J. Chem. Educ.* **1950**, *27*, 443−444.
(24) Malm, L. E. *J. Chem. Educ.* **1956**, *33*, 390−392.
(25) Basolo, F. *J. Chem. Educ.* **1980**, *57*, 761−762.
(26) Basolo, F.; Parry, R. W. *J. Chem. Educ.* **1980**, *57*, 772−777.
(27) Gorman, M. *J. Chem. Educ.* **1983**, *60*, 214−216.
(28) Zuckerman, J. J. *J. Chem. Educ.* **1986**, *63*, 829−833.
(29) Lloyd, B. W. *J. Chem. Educ.* **1992**, *69*, 866−869.
(30) Daniels, F. *J. Chem. Educ.* **1959**, *36*, 437−440.
(31) Bailar, J. C., Jr. *J. Chem. Educ.* **1989**, *66*, 537−545.
(32) Holme, T. A. (Iowa State University, Ames, IA). Personal communication, 2015.
(33) Huheey, J. E. *J. Chem. Educ.* **1972**, *49*, 326−327.
(34) Verkade, J. G. *J. Chem. Educ.* **1991**, *68*, 911−914.
(35) Mellon, E. K. *J. Chem. Educ.* **1980**, *57*, 761.
(36) Basolo, F. *J. Chem. Educ.* **1980**, *57*, 761−762.
(37) Sienko, M. J. *J. Chem. Educ.* **1980**, *57*, 765−766.
(38) Laudise, R. A. *J. Chem. Educ.* **1980**, *57*, 762.
(39) Cotton, F. A. *J. Chem. Educ.* **1980**, *57*, 768.
(40) Meyer, T. J. *J. Chem. Educ.* **1980**, *57*, 763−764.
(41) Brown, H. C.; Toy, A. D. F.; Crosby, G. A.; Mellon, E. K. *J. Chem. Educ.* **1980**, *57*, 768−769.
(42) Gray, H. B. *J. Chem. Educ.* **1980**, *57*, 764−765.
(43) In the 2015 ACS CPT guidelines, larger-scale systems are defined as synthetic polymers, biological macromolecules, supramolecular aggregates, and meso- or nanoscale materials. Students are expected to be familiar with the preparation, characterization, and physical properties of at least two of these classes of materials.
(44) Wulfsberg, G. P. *J. Chem. Educ.* **2012**, *89*, 1220−1223.
(45) Shulman, L. S. *Change* **1999**, *31*, 10−17.
(46) Halpern, D. F.; Hakel, M. D. *Change* **2003**, *35*, 36−41.
(47) Burke, K. A.; Greenbowe, T. J.; Gelder, J. I. *J. Chem. Educ.* **2004**, *81*, 897−902.
(48) POGIL: Processs Oriented Guided Inquiry Learning. https://pogil.org (accessed June 1, 2015).
(49) Peer Led Team Learning [PLTL]. https://sites.google.com/site/quickpltl/ (accessed June 1, 2015).
(50) National Center for Case Study Teaching in Science. http://sciencecases.lib.buffalo.edu/cs/ (accessed June 1, 2015).
(51) Virtual Inorganic Pedagogical Electronic Resource. https://www.ionicviper.org/ (accessed June 1, 2015).
(52) National Science Digital Library. https://nsdl.oercommons.org (accessed June 1, 2015).
(53) "Other" Resources Used for Teaching Inorganic Chemistry—Results from the 2013 Survey. https://www.ionicviper.org/2013-Inorg-Curric-Survey-Other-Resources (accessed June 1, 2015).
(54) Web Resources from the 2013 Inorganic Curriculum Survey. https://www.ionicviper.org/collection/web-resources-2013-inorganic-curriculum-survey (accessed June 10, 2015).
(55) NGSS Lead States. *Next Generation Science Standards: For States, By States*; The National Academies Press: Washington, DC, 2013.
(56) Holme, T.; Murphy, K. *J. Chem. Educ.* **2012**, *89*, 721−723.
(57) Sevian, H.; Talanquer, V. *Chem. Educ. Res. Pract.* **2014**, *15*, 10−23.
(58) Talanquer, V. *J. Chem. Educ.* **2015**, *92*, 3−9.
(59) Jamieson, E. Metals in biological systems: Who? How? and Why? https://www.ionicviper.org/five-slides-about/metals-biological-systems-who-how-and-why (accessed July 30, 2015).
(60) Eppley, H. Interpreting the solid state structure of GaAs. https://www.ionicviper.org/problem-set/interpreting-solid-state-structure-gaas (accessed August 25, 2015).
(61) Crowder, K. N. Solid state models with ICE solid state model kits. https://www.ionicviper.org/classactivity/solid-state-models-ice-solid-state-model-kits (accessed July 30, 2015).
(62) Gunn, E. Visualization of zeolite structure. https://www.ionicviper.org/class-activity/visualization-zeolite-structure (accessed August 25, 2015).
(63) Plass, K. PVEducation.org: A resource for teaching solid-state chemistry and photovoltaics. https://www.ionicviper.org/web-resources-and-apps/pveducationorg-resource-teaching-solid-state-chemistry-and-photovoltaics (accessed July 30, 2015).
(64) Johnstone, A. H. *J. Comput. Assist. Learn.* **1991**, *7*, 75−83.
(65) Johnstone, A. H. *J. Chem. Educ.* **2010**, *87*, 22−29.
(66) Magnusson, E. *J. Am. Chem. Soc.* **1990**, *112*, 7940−7951.
(67) Lee, J. P. Engaging students in the inorganic chemistry classroom with well-defined group activities and literature discussions. In *Addressing the Millennial Student in Undergraduate Chemistry*; ACS Symposium Series; Potts, G. E., Dockery, C. R., Eds.; American Chemical Society: Washington, DC, 2014; Vol. *1180*, pp 25−45; 10.1021/bk-2014-1180.ch003.
(68) Bruehl, M.; Pan, D.; Ferrer-Vinent, I. J. *J. Chem. Educ.* **2015**, *92*, 52−57.
(69) Eppley, H. The unusual [F3SNXeF]$^+$ cation with a Xe−N bond: Adapted for an intro question! https://www.ionicviper.org/problem-set/unusual-f3s-nxef-cation-xe-n-bond-adapted-intro-question (accessed July 30, 2015).
(70) Geselbracht, M. Molecular structure of new explosive phosphorus triazides. https://www.ionicviper.org/problemset/molecular-structure-new-explosive-phosphorus-triazides (accessed July 30, 2015).
(71) Geselbracht, M. Tetrahedral tellurate. https://www.ionicviper.org/literature-discussion/tetrahedral-tellurate (accessed July 30, 2015).
(72) Young, K.; Saha, A.; Rowe, G.; Yang, L.; Williams, N. S. B.; Holbrook, R.; Collins, S. Modeling post-translational modification in cobalt nitrile hydratase with a metallopeptide from Anne Jones. https://www.ionicviper.org/literature-discussion/modeling-post-translational-modification-cobalt-nitrile-hydratase (accessed July 30, 2015).
(73) Reig, A.; Chan, B.; Vaughn, D., II; Nguyen, M. A. T.; Ricciardo, R.; McCaffrey, V.; Flomer. W. Tuning the band gap of CZT(S,Se) nanocrystals by anion substitution. https://www.ionicviper.org/literaturediscussion/tuning-band-gap-cztsse-nanocrystals-anion-substitution (accessed July 30, 2015).
(74) PhET: Interactive Simulations. https://phet.colorado.edu/ (accessed July 30, 2015).
(75) *Discipline-based education research: Understanding and improving learning in undergraduate science and engineering*; Singer, S. R., Nielsen, N. R., Schweingruber, H. A., Eds.; National Academies Press: Washington, DC, 2012.
(76) *Reaching students: What research says about effective instruction in undergraduate science and engineering*; Kober, L., Ed.; National Academies Press: Washington, DC, 2015.
(77) Baker, L. A.; Chakraverty, D.; Columbus, L.; Feig, A. L.; Jenks, W. S.; Pilarz, M.; Stains, M.; Waterman, R.; Wesemann, J. L. *J. Chem. Educ.* **2014**, *91*, 1874−1881.
(78) Taber, K. S. *Chem. Educ. Res. Pract.* **2013**, *14*, 156−168.
(79) Great Expectations: The Undergraduate Inorganic Curriculum. http://www.ionicviper.org/forum-topic/great-expectations-undergraduate-inorganic-curriculum (accessed August 30, 2015).

DOI: 10.1021/acs.inorgchem.5b01320
Inorg. Chem. 2015, 54, 8859−8868