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Textbook Treatments of Electrostatic Potential Maps in General and Organic Chemistry

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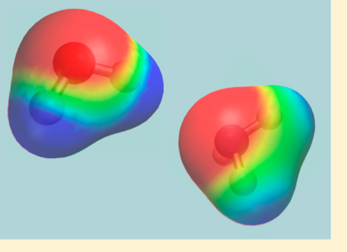
Supporting Information

ABSTRACT: Electrostatic potential maps (EPMs) allow for representation of key molecular-level information in a relatively simple and inexpensive format. As these visualizations become more prevalent in instruction, it is important to determine how students are exposed to them and supported in their use. A systematic review of current general and organic chemistry textbooks (N = 45) determined how frequently EPMs were presented in texts, how well distributed EPMs were across chapters, whether EPMs were included in end-of-chapter problems, and the types of conceptual instructional support provided to students when first exposed to them. Analysis demonstrated great variance in the use of EPMs. Most, but not all, textbooks presented at least one image, yet the prevalence and integration across texts varied greatly, owing in part to content differences between general and organic texts. Many texts provided minimal conceptual support and did not include EPMs in end-of-chapter problem sets. Overall, little consensus emerged as to how often EPMs should be used, and the sorts of instructional supports or student practice offered to scaffold the use of EPMs. These findings suggest a need for examining the supports that foster effective comprehension and use of EPMs, and more generally, obtaining data that inform the design and implementation of emerging instructional supports.



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Electron transfer and partial transfer (sharing) are the heart of chemistry. But these molecular-level processes cannot be directly observed by students and practitioners of chemistry. Because of this, considerable effort has been invested in the development of visualizations meant to represent these and other processes normally inaccessible to the naked eye, as evidenced by the contents of edited volumes[1,2] and several papers recently published in this *Journal*.[3−5] For general and organic chemistry courses, electron representations are often based on Lewis structures in which nonbonded electrons are shown as dots (either single dots or pairs of dots) and bonded electrons are shown via bond lines (two electrons for each single line). From these electronic representations, students are provided with a visual bookkeeping of all valence electrons. Although Lewis structures are useful for bookkeeping, they are not designed to depict electron *distribution* in a molecule. Thus, properties related to electron distribution such as bond polarity, partial charges, and chemical reactivity are not readily derived from Lewis structures alone. Rather, students would likely need to infer these properties based on knowledge about electronegativity, inductive effects, and resonance, and then apply that knowledge to the representations of Lewis structures. Given the challenge of making such inferential connections,[6,7] students may benefit from visualizations that more directly represent electron distribution, such as electrostatic potential maps (EPMs). EPMs are designed to represent electron distribution via schematic color mapping. Typically, an electron isosurface is wrapped around a representation of a molecule, and the EPM color codes surface areas as red for areas enclosing high electron density (net negative charge), blue for areas containing low electron density (net positive charge), and green or white for areas in which the enclosed negative electron charge and the positive core charge balance (overall neutral charge).

The visual characteristics of EPMs have driven instructional calls for their use in educational settings. For example, Shusterman and Shusterman proposed the use of EPMs in general and organic chemistry courses, as these representations are accessible to students and easy to produce.[8] Their paper

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described techniques for the use of EPMs in a number of areas. The authors summarized (ref 8, p 776):

> *Electronic structure plays an important role throughout chemistry, affecting molecular size, shape, bonding, stability, reactivity, and many other characteristics. Unfortunately, relatively few of these subjects have been included in traditional general chemistry curricula because the tools normally used to describe electronic properties, namely, "orbital" theories, are so difficult to use. We believe that computer-generated electron density models provide a student-friendly option for describing electronic structure and for studying the role of electronic structure in a wide variety of chemical phenomena.*

EPMs might be useful for understanding certain chemical concepts to the extent that the visualizations facilitate nonverbal, concrete representations of abstract concepts.[9] For example, a text could verbally describe the reactivity of carbonyl compounds, explaining that the carbon is more electrophilic owing to polarization of the C═O bond. But this concept may be difficult to comprehend based on a verbal description alone, whereas an EPM could facilitate the display of electron distribution and clearly indicate the preferred electrophilic site from the color-coded regions. Provided with an EPM for water, students can easily see that a positive charge is found in the area where the hydrogen atoms are closer than might be expected from a simple Lewis diagram, and that a negative charge is found around the oxygen atom. For concepts such as those described above, in which spatial information is particularly relevant, researchers have repeatedly advocated that visualizations and multimedia displays can help learners integrate verbal and spatial representations of concepts[1,2,7] and lead to long-term learning gains.[10]

Specifically in support of calls for the use of EPM visualizations, there is some evidence of improved learning as a function of their use. One relevant and promising project investigated the use of EPMs with animations on students' understandings of molecular polarity and the intermolecular forces involved in miscibility.[11] Employing a quasi-experimental design with second-semester general chemistry classes, students in one class received EPMs and animations in the course of their instructional experiences. Instruction that included the use of EPMs and animations led students to demonstrate significantly better conceptual test performance as compared with the performance of students in control classes. Thus, EPMs may provide an opportunity for improving conceptual understanding with regard to the topics of polarity and miscibility.

On the basis of these theoretical and evidence-based recommendations for implementing EPMs, instructional designers, instructors, and textbook designers may want to include the representations in their learning materials. In the present study, we reviewed current editions of general and organic textbooks to determine the extent to which EPMs have been adopted in textbooks to date. Research has convincingly indicated that comprehension of chemical visualizations is not automatic, but requires a good deal of practice and chemical knowledge to support their use.[12] Because of this, we also explored some of the types of instructional supports that were potentially provided to students when EPMs are presented.

First, students may benefit from instruction that emphasizes the conceptual basis for EPM representations. Crucial differences exist between the learning that can result from rote memory activities versus deeper, more conceptual strategies.[13] For example, just asking students to consider the memorized idea that red is negative and blue is positive in EPMs requires more shallow cognitive processing than asking students to use the data extracted from the EPMs on problem solving or transfer tasks. These latter tasks encourage the construction of inferences and the activation of knowledge associated with more effective learning strategies and outcomes.[10,14] While textbooks can provide students with information about the color-mapping relationships in EPMs, deeper conceptual understandings are more likely to derive from instruction explicitly targeting the chemical relationships underlying electron distribution. Thus, we were interested in the types of conceptual-level, instructional supports provided in the textbooks.

Second, it is crucial to note that with any new instructional technique, including teaching with EPMs, assessment often motivates and guides learning.[15−17] If an instructor does not consider an idea or method important enough to assess in some way, then students quickly learn to ignore it or to treat it as supplemental rather than crucial to learn. Assessment can also drive instructional strategies and decisions, encouraging instructors to provide supports for particular activities and neglecting others, thus influencing both teacher and student practices.[18] Finally, explicit practice and testing can even have a direct influence on learning, making assessments useful and effective opportunities for acquiring and understanding target concepts.[19,20] For these reasons, we examined whether textbooks offered assessment opportunities in their implementations of EPMs.

We examined EPMs as they are actually presented in contemporary college-level chemistry textbooks by evaluating authors' design decisions, such as the level of instructional support offered or the inclusion of end-of-chapter problems. This examination was meant to gauge the perceived value of EPMs as instructional tools. Inclusion of EPMs across a variety of texts would indicate that students are being regularly exposed to them with the ostensible goal of fostering chemical understanding and interest. The inclusion of conceptual instructional supports for students' interpretation of EPMs would indicate such activity is considered an important instructional objective. Finally, the inclusion of end-of-chapter problem sets requiring the use of EPMs would indicate a goal for students to learn to use and apply EPMs when interpreting molecular properties.

Recent research in our lab has demonstrated that organic chemistry students do not routinely adopt EPMs for problem solving when more familiar ball-and-stick plots are available, even after reading a three-page description outlining the nature and function of EPMs. However, participants with prior chemistry knowledge developed fluency with EPMs after repeated opportunities to work with the representations, demonstrating the utility of practicing with them.[21] Thus, it is important to determine whether and how EPMs are being presented to students, how the information is conveyed relative to chemistry content, and whether textbooks offer opportunities to practice using EPMs. While the current analysis focused specifically on EPMs, we also hoped a survey of their implementation would offer a relevant case study for considering whether and how emerging instructional supports are adopted for use in educational materials.

■ METHOD

Materials

We sampled current editions of general chemistry (N = 24) and organic chemistry (N = 21) textbooks available to the content

Table 1. EPM Content Data for General Chemistry Textbooks

General Chemistry Textbook Authors (edition, year) N = 24	Special Section Present?	Number of EPM			Proportion of Chapters Including EPM(s), %
		Cases	Problems	Chapters	
Atkins and Jones (5, 2009)	Yes	35	0	6	32
Averill and Eldredge (1, 2006)	No	43	0	6	25
Brady and Senese (5, 2007)	No	0	0	0	0
Brown et al. (12, 2011)	No	11	0	2	8
Burdge (1, 2009)	Yes	18	0	4	16
Chang (Essential Concepts) (5, 2007)	No	30	0	5	23
Chang and Goldsby (11, 2012)	No	38	0	7	29
Ebbing and Gammon (9, 2009)	No	37	1	14	61
Gilbert et al. (3, 2011)	No	13	12	3	14
Jones and Atkins (4, 2000)	No	8	0	1	5
Kotz, Treichel, and Townsend (8, 2011)	Yes	40	14	5	22
Masterson and Hurley (6, 2009)	No	0	0	0	0
McMurry and Fay (5, 2007)	No	59	3	5	21
McMurry and Fay (Atoms First) (1, 2010)	No	52	3	4	18
Moore, Stanitski, and Jurs (4, 2010)	No	8	0	4	18
Olmstead and Williams (4, 2004)	No	9	0	5	23
Oxtoby, Gillis and Campion (6, 2007)	No	12	0	2	9
Petrucci et al. (10, 2010)	Yes	63	15	7	25
Reger, Goode and Ball (3, 2009)	No	24	0	2	9
Silberberg (5, 2008)	No	74	0	5	22
Tro (2, 2010)	No	19	0	5	22
Whitten et al. (9, 2010)	Yes	302	23	14	50
Zumdahl and Zumdahl (Atoms First) (1, 2011)	Yes	12	34	1	5
Zumdahl and Zumdahl (8, 2008)	Yes	10	0	1	5
Mean	—	38.21	4.38	4.50	19.12
SD	—	59.83	8.87	3.60	14.46

Table 2. EPM Content Data for Organic Chemistry Textbooks

Organic Chemistry Textbook Authors (edition, year) N = 21	Special Section Present?	Number of EPM			Proportion of Chapters Including EPM(s), %
		Cases	Problems	Chapters	
Brown et al. (6, 2012)	Yes	43	2	14	47
Brown and Poon (3, 2008)	Yes	37	0	12	55
Bruice (6, 2010)	Yes	152	1	19	61
Bruice (essentials) (2, 2009)	Yes	88	1	13	62
Carey (7, 2008)	Yes	120	1	29	100
Carey and Giuliano (8, 2011)	Yes	116	2	27	100
Clayden et al. (1, 2001)	No	0	0	0	0
Dewick (1, 2006)	No	0	0	0	0
Ege (5, 2004)	No	0	0	0	0
Fox andWhitesell (3, 2004)	No	0	0	0	0
Hornback (2, 2006)	Yes	56	0	10	36
Jones and Fleming (4, 2010)	No	0	0	0	0
Klein (1, 2006)	Yes	27	1	14	52
McMurry (biology) (2, 2011)	Yes	153	13	16	64
McMurry (7, 2011)	Yes	168	11	22	71
McMurry (Fundamentals) (7, 2011)	Yes	101	9	13	76
Smith (3, 2011)	Yes	64	2	15	50
Solomons and Fryhle (10, 2011)	Yes	75	3	16	64
Sorrell (2, 2006)	No	0	0	0	0
Vollhardt and Schore (6, 2011)	No	100	0	20	77
Wade (6, 2006)	Yes	33	0	10	38
Mean	—	63.48	2.19	11.90	45.45
SD	—	56.49	3.84	9.08	33.51

experts in our research group and their colleagues. The authors and edition numbers for these texts are presented in Tables 1 and 2. A full reference list of the sampled texts is available as Supporting Information. This sample is by no means exhaustive, given the range of textbook options available to instructors. However, it included many of the most commonly adopted texts, and

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represented a large enough sample of observations to obtain sufficient statistical power to compare general and organic text categories.[22] We were especially interested in sampling both textbook categories to determine whether there might be differences in how the two subdisciplines use and support EPM presentations.

Coding

Sample EPMs and the kinds of descriptions that could accompany the visualizations are provided in Figure 1. EPM

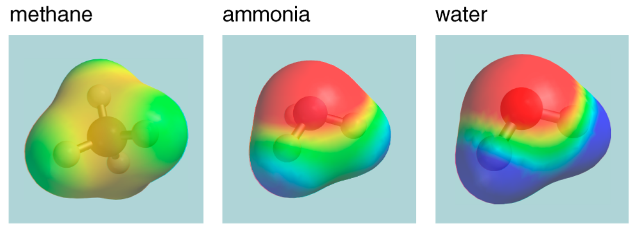

Figure 1. Example electrostatic potential maps for methane, ammonia, and water. Accompanying text could discuss how these images illustrate that the uneven distribution of electrons results in potential surfaces that have distinct localized charges. The uniform green color of methane indicates a uniform electron distribution. The red and blue portions of ammonia indicate electron concentration and depletion, respectively. The color distribution in water indicates an even greater localization at the oxygen and depletion at the hydrogen atoms. Water and ammonia have permanent dipoles; methane does not.

content was coded for each chapter in every book, using a simple visual content analysis.[23] Content analysis involves the quantitative coding of representation use in media in order to describe content and to test hypotheses regarding different representations or media types. Our coding occurred on three dimensions:

1. The number of cases of EPMs displayed in the text, counting multiple cases even within the same figure
2. The number of cases appearing in end-of-chapter problems
3. The presence of conceptual instructional supports for EPMs in a *special section*

The case coding (dimensions 1 and 2) was objective and straightforward, representing the relative priority of EPMs in text and end-of-chapter problems. For example, Figure 1 contains three cases of EPMs. End-of-chapter questions may use single or multiple examples of EPMs, as in Figure 1, in support of a particular conceptual question (e.g., to ask students to explain why water has a higher boiling point than methane). Coding for special sections required a more extensive delineation, and so had to meet three criteria. Special sections mapped the colors of an EPM with relative charges, described the nature of EPMs with regard to electron or charge distribution, and gave multiple examples using different atoms and molecules. As an example, the accompanying text in Figure 1 meets these criteria by mapping charges to colors, relating these colors to the relative distribution of electrons, and comparing three examples of EPMs. These special sections typically were presented as either a supplemental text box or demarcated by a section heading, though these design decisions were not required for coding. Most textbooks without special sections outlined the color-mapping system in a figure caption on the first occurrence of an EPM without providing any other instructional support or comparing cases, so these were not coded as a special section. The presence or absence of a special section was coded by two individuals for each text, with final determinations reached by consensus. To establish inter-rater reliability for this coding scheme, three additional trained research assistants applied the scheme to a random subsample of 11 texts (24.44% of the sample), with each pair of coders reaching agreement on either 10 (90.90%) or 11 (100%) of the codes.

■ RESULTS AND DISCUSSION

Table 1 presents the coding data for each general chemistry textbook, and Table 2 presents the coding data for each organic chemistry textbook. When appropriate, we assessed the difference between general chemistry and organic chemistry texts. These analyses used independent-samples t-tests when the dependent variables were continuous (e.g., number of cases). When necessary, we corrected for unequal variance in the samples based on Levene's test for equality of variance. We also calculated Cohen's d as a measure of effect size whereby the value of d reflects the size of an effect relative to the pooled standard deviation (i.e., a d value of 0.50 reflects an effect of one-half SD).[22] When the dependent variables were categorical (e.g., the inclusion or exclusion of a special section), we compared general and organic books using Pearson's χ^2 tests.

Cases of EPM Use

One purpose of this textbook review was to determine the prevalence or priority of EPMs in textbooks, and to determine whether this prevalence differs for general and organic texts. Images of EPMs were found in most textbooks we examined, that is, in 22 out of 24 (91.67%) general chemistry books and in 15 out of 21 (71.43%) organic chemistry books. Inclusion of EPMs did not differ significantly for general and organic books, $\chi^2(1, N = 45) < 1$. Clearly EPMs appear in many chemistry textbooks, though it is striking that 8 of the 45 (17.78%) textbooks did not include them. The implementation of EPMs, then, is common but not universal. When EPMs appeared, their depiction was similar across books, with most using the EPM overlaying a ball-and-stick model. Examples of hydrofluoric acid, water, and ammonia were common in the introduction to EPMs, although the organic textbooks moved quickly to alkanes and alcohols.

Despite the regular inclusion of EPM visualizations, the number of cases of their use varied greatly, with a range of 8−302 images in general chemistry textbooks (SD = 59.83), and 27−168 images in organic chemistry textbooks (SD = 56.49). We note that one textbook (Whitten, Davis, Peck, and Stanley, 2010) was a clear outlier among general chemistry texts, offering an upper bound of 302 cases (over 4 SD above the mean). Despite our observation that six organic textbooks completely left out EPMs, organic textbooks actually included nominally but not significantly more visualizations than did general chemistry books, for which only two textbooks did not include EPMs: $t(43) = 1.45$; $p = 0.15$. This calculation included the general chemistry textbook by Whitten et al. (2010). Excluding this outlier text revealed a significantly greater number of cases of mean EPM use for organic books: $M = 63.48$, SD = 56.49, as compared to general chemistry books, $M = 26.74$, SD = 21.02; $t(25) = 2.81$, $p = 0.01$, $d = 0.86$. One possible reason for this pattern is that electronic structure is key to more topics within organic than general chemistry. For example, EPMs may be useful for understanding the electronic structure of functional groups, chemical reactivity, relative atomic charges, and resonance, all of which may be more prominent in organic than general chemistry curricula. EPMs may thus be used for a wider *variety* of topics within organic texts. If this is true, then we

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should expect to not only see *more* cases of EPMs in organic texts, but also more consistent integration of EPMs across chapters.

Integration of EPMs

Beyond the frequency of EPM inclusions, determining the consistency of EPM use across chapters within each textbook provides an indication of the extent of their integration with respect to textbook contents. For general chemistry textbooks, integration varied considerably, with most textbooks presenting EPMs in less than one-fourth of the chapters, and others presenting them in almost two-thirds of the chapters. For the general chemistry textbooks that contained EPMs, 20 out of 22 (90.90%) included them in the chapter on bonding, followed by 13 out of 22 (59.09%) including EPMs in the chapter on organic chemistry, and 12 out of 22 (54.54%) in the chapters on liquids and acids−bases. When organic chemistry texts included EPMs, they tended to integrate them throughout the text (ranging from 36−100% of the chapters). Most organic texts included EPMs in at least half of the chapters (i.e., 12 out of 15; 80%), usually when describing the structure of a functional group and the reactions of that group. Consistent with the observations described above, the average number of chapters including EPMs was significantly higher for organic textbooks than for general textbooks: $t(26) = 3.50$, $p = 0.001$, $d = 1.02$. Thus, it appears that EPMs are more consistently used in organic than general chemistry texts, presumably because the representation of electronic structure might be considered more relevant to a wider range of topics in the organic chemistry curriculum.

Use of EPMs in End-of-Chapter Assessments

Besides examining the inclusion of EPMs in the textbooks, we also examined whether they appeared in end-of-chapter problems. As examples, problems that involved EPMs asked students to use them to construct Lewis dot structures, to compare formal charges, and to identify specific molecules, dipole moments, boiling point ranking, relative vapor pressure, polarity, or electron density. These questions required a combination of inferences based on the EPMs and the identification of chemical features.[21]

EPMs were generally less likely to appear in the problem sets than in the body of the text. Only 8 out of 24 (33.33%) general chemistry, and 11 out of 21 (52.38%) organic chemistry books used EPMs in their problem sets. The mean use of EPMs in problem sets did not vary based on the course level of the book: $t(32) = 1.10$, $p = 0.28$.

Instructional Support Sections

Finally, textbooks differed in their inclusion of a special section offering instructional support for students to learn how to use EPM visualizations. Only 7 out of 24 (29.17%) general chemistry texts included such a section, while 14 out of 21 (66.67%) organic textbooks offered a special section. Instructional support sections appeared significantly more often in organic than general chemistry textbooks: $\chi^2(1, N = 45) = 6.33$, $p = 0.01$. It is unclear why organic texts were more likely to include these sections than were general chemistry texts, but this might be tied to the more frequent and consistent use of EPMs in organic than general texts. Textbook designers who have identified EPMs as a useful tool for communicating a variety of topics may be more likely to consider the benefits of instructional supports scaffolding their use. To address these and other potential connections between our codes, we next discuss the co-occurrence of support sections and the use of EPMs in text and end-of-chapter problems.

Cases, Problems, and Support Sections

Our final analysis considered the combined presentations of each of the separate content assays of EPM implementations. Whereas only 4 of the 24 (16.67%) general chemistry textbooks offered all three of these EPM elements, 11 of the 21 (52.38%) organic chemistry textbooks included all three. This difference was significant, $\chi^2(1, N = 45) = 6.43$, $p = 0.01$, suggesting that organic textbooks were more likely than general chemistry textbooks to comprehensively implement EPMs in their content.

Substantial correspondence emerged between instructional support sections and end-of-chapter problems. Fifteen out of 21 (71.42%) texts that included a special section also included EPMs in problems, while only 4 out of 24 (16.67%) of the texts without special sections did so: χ^2 $(1, N = 45) = 13.77$, $p < 0.001$. Only four general chemistry texts and none of the organic chemistry texts included EPMs in the chapters and end-of-chapter problems without also including a special instructional section. Finally, only 3 of the 24 (12.50%) general chemistry textbooks and 3 of the 21 (14.29%) organic texts included EPMs in the chapters and in a special instructional section, but failed to include them in end-of-chapter problem sets. These data indicate substantial correspondence between the use of EPMs and the instructional supports provided for them. However this was not always the case, with some texts integrating EPMs into text content yet opting to leave out either special instructional support sections, end-of-chapter problems, or both.

■ SUMMARY AND IMPLICATIONS

Summary

Our examination indicated that textbook designers differ in the relative emphasis they offer for EPM visualizations in their textbooks. They differ in how often they present the visualizations, whether or not they provide conceptual guidance on the use or interpretation of the visualizations, and whether they offer practice using the visualizations to solve problems. We also observed instances in which texts presented no EPMs at all, while at the other extreme one text presented over 300 cases across 14 different chapters. A range of possibilities clearly exists for including these visualizations in textbook contents, providing a variety of options for authors and instructors alike. Compared with general chemistry textbooks, organic textbooks presented EPMs more frequently overall, integrated them across more chapters, and provided more instructional sections for supporting their use, although they did not include EPMs more often in end-of-chapter problem sets. It might not be particularly surprising that organic chemistry texts more fully integrate EPMs into their contents. Bond polarity is a key point to consider when working out chemical reactivity based on functional groups, relative atomic charges, resonance, and reaction mechanisms, all of which underlie core competencies and constructs in organic chemistry. However, calls to use EPMs have suggested that they are nevertheless useful for *both* organic and general chemistry topics.[8]

One striking finding from this analysis involved the regularity of cases for which readers could be exposed to EPMs but were provided with only minimal or no conceptual support for using them based on either instructional sections or end-of-chapter practice problems. Research has shown that understanding the kinds of information and inferences these visualizations afford, beyond mapping features (e.g., colors) to referents (e.g., relative charges), requires explicit instruction and practice.[21] Future research may help to determine the types of supports and practice that are most helpful for students at different levels. For example, instructors may focus on fostering representational competence, asking students to choose or construct representations that will be most useful for reasoning about particular chemical problems or relationships.[12] Activities could focus on highlighting *when* and *why* EPMs prove more or less useful, and when other representations may be more appropriate or informative, thus facilitating fluency with regard to their effective use.[21,24] Consider, for example, efforts to integrate the dynamic use of multiple representations via learning progressions.[6] These types of inclusions may help to supplement any textbook-derived supports.

We also observed relatively few opportunities for practicing EPMs in end-of-chapter problems. Unless integrated into assessments such as homework, quizzes, exams, and standardized tests, these types of representations may be ignored by students and instructors. We note that we did not examine the test banks that accompany these textbooks, and thus it may be interesting to evaluate whether EPMs are present in the exam questions over and above any inclusion or exclusion in the textbook contents. Perhaps informing this issue, we have not witnessed the implementation of EPMs in commercially available online homework, tests, or quizzes to date. While EPMs could be easily integrated in online resources to avoid color-printing issues, they do not appear to be used regularly at this point. Other visual supplements, such as particulate-level drawings, first appeared in textbooks before being integrated into homework and exams.[25] It may be that implementations of EPMs will unfold in a similar way.

Implications

An important issue for textbook authors and instructional designers involves identifying and implementing the most effective means for representing electronic structure for novice chemistry coursework. Electrostatic potential maps provide valuable information about electronic structure that proves accessible to beginning level students, as evidenced by existing studies,[8,11,21] which raises the question as to why they are not more consistently used. If we opt to employ EPMs as an instructional tool, students likely need support for understanding what is being represented beyond a simple color-coding legend, particularly if the goal is to support comprehension and problem solving that necessitates going beyond the visual characteristics inherent in the displays. This could be supported by integrating representation use into learning progressions.[6] Finally, if EPMs are important enough to be used in instruction, they likely should also appear in assessment activities, such as the kinds that appear in end-of-the-chapter problem sets. Research from our laboratories suggests that even high-performing students require practice with EPMs to effectively use them.[21] Thus, problem sets can communicate the importance of EPMs while also providing practice and feedback that may facilitate learning.[19,20] Most textbook designers seem to have considered EPMs as useful, or at least interesting enough to include in their texts. But they appear to disagree about how and how often to include them in learning materials, whether to provide instructional guidance and practice. Future work should examine whether these design decisions have consequences for student learning.

Beyond the inclusion of instructional sections and end-of-chapter problems in textbooks, additional instruction in the use of EPMs could be provided by instructors. For example, instructors might consider giving students opportunities to practice putting these and other visualizations to use and to consider their utility for different purposes. These kinds of activities can supplement the use of textbook content, but perhaps more importantly serve as important experiences for establishing student proficiency with visualizations. This includes helping students build the skills necessary to relate different kind of representations to each other (i.e., representational fluency), and to consider when particular visualizations might be most effective for completing tasks and deriving understandings.[6,21]

The current project can offer a useful case study for contemplating the adoption of instructional supports in educational materials, as well as the trajectories with which novel instructional designs are implemented in coursework and course supports. EPMs only represent one type of visualization implemented via texts or other educational materials. For example, molecular polarity can be made explicit through other representations such as isosurfaces or colored lobes.[26] How students integrate EPMs with other representations and how comprehension of these complex displays is supported is an important avenue for future research.

We focused here specifically on textbooks because they are a core means of providing students with instructional experiences, and they are readily accessible for instructors to evaluate with respect to their pedagogical decisions. Of course many issues need to be considered in the selection and development of textbook and supplemental instructional materials, including cost, author and publisher preferences, designer and illustrator toolsets, scope and comprehensiveness of the intended contents, and so on. The goal of instructional design, including the development of textbooks, should be to implement the most effective methods and techniques for supporting students' understanding of core content. Doing so may necessitate more effective interactions between educational researchers, curriculum and materials developers, teachers and instructors, and formal or informal dissemination systems (conferences, training settings, journal articles, developer workshops, etc.). These interactions help to ensure that effective research and theory are put into effective practice. EPMs as evaluated in the current paper offer insight into the kinds of considerations at play in the design and implementation of instructional methods that, we argue, are not limited to pedagogical decisions about visualizations.

■ ASSOCIATED CONTENT

Supporting Information

Reference list of all general and organic textbooks reviewed. This material is available via the Internet at http://pubs.acs.org.

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Notes

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