Multiple-Choice Questions for Teaching Quantitative Instrumental Element Analysis: A Follow-Up

Journal Article

Author(s):
Schwarz, Gunnar

Publication date:
2023-10-10

Permanent link:
https://doi.org/10.3929/ethz-b-000634344

Originally published in:
Journal of Chemical Education 100(10), https://doi.org/10.1021/acs.jchemed.3c00061

JOURNAL OF CHEMICAL EDUCATION

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Communication

Multiple-Choice Questions for Teaching Quantitative Instrumental Element Analysis: A Follow-Up

Gunnar Schwarz*

Cite This: J. Chem. Educ. 2023, 100, 4099−4105

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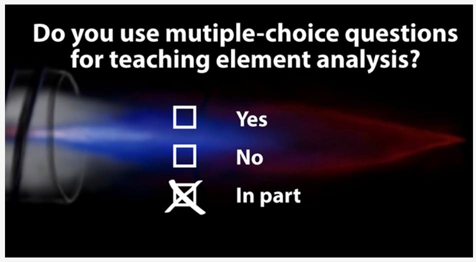
ABSTRACT: This communication follows up to two previously published manuscripts concerning classroom response systems and multiple-choice questions. Here, more than 250 multiple-choice and true-false items for the basics in quantitative instrumental element analysis with keys and brief explanations are presented. Guidelines for designing questions for exams are revisited for developing exercise material, and the generation of distractors based on responses to open-ended questions is investigated within a routine teaching context.



KEYWORDS: *Second-Year Undergraduate, Upper-Division Undergraduate, Analytical Chemistry, Testing/Assessment, Atomic Spectroscopy, Quantitative Analysis*

■ INTRODUCTION

Questions, tasks, and problems, which are subsequently subsumed under the term questions, in varied forms and scopes play a vital role in prompting students to engage with the material, practice problem-solving skills, or assess their (intermediate) learning outcomes. There is a broad consensus that questions promote learning, and there are numerous approaches on how to activate and engage students with questions.[1−5]

In addition to their continued use in exams, multiple-choice questions (MCQs) have come to the forefront with the recently increased utilization of classroom response systems (CRSs), as CRSs are primarily used with MCQs. Compared to open-ended questions (OEQs), MCQs are better suited for involving a large number of students for swift responses and response evaluation.[6−8] However, MCQs only require students to select options that are already presented, not create their own response.[7,9] Still, MCQs can be a valuable option for instructors to engage students. Yet, much of what is available to support instructors with MCQs is often derived from and specifically related to exams[10−14] and not exercises. It is worth considering how those may differ for the exercise material.

Haladyna et al.[11] pointed out that their guidelines for MCQ phrasing should be taken as advice and not immutable rules. Moreover, exam items often result from learning objectives of a particular course.[15] However, in the classroom, MCQs can both be used to engage students with the content and receive feedback in their performance. Questions in a class discourse may arise spontaneously, e.g., as a question or response from a student, to tackle prior knowledge, opinions, or justifications for a proposition. Thus, the aim, content, and format of in-class questions can be more varied than for exams.

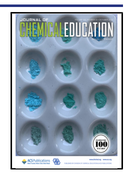
Although many examples of MCQs and OEQs may be found for basics in general chemistry and all branches of chemistry, the list grows thinner for instrumental and advanced analytical chemistry, which may be presented to students from their second year in higher education onward. Also, approaches like student-generated questions[7,16−18] or computer-generated questions[19] have not been widely adopted, which may change with text generative models.[20,21]

This contribution follows up on two recent publications, one focusing on CRSs[6] and the other on MCQs for CRSs.[22] Here, numerous MCQs for quantitative instrumental element analysis are offered. Guidelines for MCQs are revisited with respect to their use in in-class discourse or worksheet exercises. Also, an investigation on the feasibility of phrasing MCQ distractors from responses to OEQs within a routine teaching environment is presented.

■ A COLLECTION OF MORE THAN 250 ITEMS

Supporting Information Part A contains a list of MCQs developed over the last several years for a course in quantitative instrumental element analysis (see Supporting Information Part B). First, there are single-choice questions (A-type MCQs), mostly used with a CRS during the lectures.[6] The remaining items are true-false items, which were used as kprime questions in worksheets and exams. Kprime (also k′) questions are a

Received: January 19, 2023
Revised: August 24, 2023
Published: September 7, 2023



https://doi.org/10.1021/acs.jchemed.3c00061
J. Chem. Educ. 2023, 100, 4099−4105

variation of the multiple true-false type for which four statements need to be assessed individually (Box 1).[23] Those should not be confused with K- or X-type questions, which suffer from flaws due to cluing and guessing, respectively.[23] The difference in X-type questions is in the grading procedure and not inherently relevant for ungraded exercises. Single statements of kprime questions may also be given individually to students or, if only one key is present, as a single-choice question. Table S1 (Supporting Information Part B) provides an overview of common MCQ types with examples.

Box 1. Example questions. All questions were translated from German. Keys are marked with an asterisk (*). See text for details.

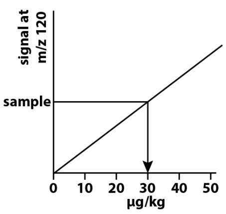
Question 1. Example of a kprime-type question. What increases the spectral resolution of an ICP-MS instrument?

True	False	
□*	□	Smaller slits in a sector field instrument
□	□*	Using a dual mode detector with analog and pulse counting
□	□*	Detection of barium at m/z 138 instead of 137.
□*	□	Increase the length of the quadrupole for an ICP-QMS

Question 2. Silver has a mass of 107.87 g/mol. At which m/z do you detect silver with ICP-MS?

A 106
B* 107
C 108
D* 109

Question 3. You quantify tin in a sample with ICP-MS and external calibration at m/z 120. The isotope abundance of ^{120}Sn is about 33%. The calibration for the signal at m/z 120 indicates a mass fraction of 30 µg/kg [see figure below]. What is the mass fraction of tin in the measurement aliquot?



A 90 µg/kg
B 60 µg/kg
C* 30 µg/kg
D 10 µg/kg

Question 4. Chocolate was digested in a closed vial under pressure using nitric acid and hydrogen peroxide using a microwave system. What constitutes the main matrix of the analyte cadmium in the prepared solution after the digestion of chocolate?

A cacao, sugar, fat
B* water
C cadmium ions
D no matrix

Question 5. How do you prepare a sample of salmon to differentiate between and quantify organic mercury species?

A microwave digestion using HCl and H_2O_2
B microwave digestion using HNO_3 and H_2O_2
C microwave digestion using HNO_3
D* no digestion

Counting four items per kprime question set, this collection comprises over 250 items with answer keys and brief explanations. To the best of the author's knowledge, this is the most comprehensive compilation of MCQs for this subject. Questions regarding two topics, namely, the scope of methods and X-ray fluorescence spectroscopy (XRF), contain the same stem and are listed separately.

Scope Questions

An often implicit skill to develop during any course is whether a problem or question can be solved by using the models or methods presented to counteract the hammer-nail bias;[24] i.e., students may treat every problem encountered with the methods covered in a course without reflecting on applicability. While lectures, textbooks, and other course materials contain many examples of applications that illustrate the relevance and connections between methods and concepts, the limitations of methods may be neglected. The two-sided questions that address this issue are here referred to as "scope questions". To answer correctly, students need to know the scope of the methods of (instrumental) element analysis presented. For example, these methods are not suited for organic compounds consisting only of hydrogen, carbon, oxygen, and nitrogen as such elements are difficult to detect or quantify, if at all. In addition, while the methods can detect and quantify metals and metalloids, they are not able to derive other analyte or sample properties, such as toxicity, for which other approaches are required. Another distinction is based on the fact that element analysis can use information obtained through other approaches, such as an acceptable daily intake (ADI) value, but it cannot generate this information by itself. For example, the lead content in wall paint may be quantified but not the tolerable daily intake of lead or lead compounds.

Since 2018, a set of four items from the scope have been used at the beginning of the written exams, with the items varying each year. Figure 1 displays the rates of key selection from 2018 to 2022. The lower rates of key selections in 2018 and 2020 were dominated by two items ("How high is the tar content in cigarette smoke?" and "Differentiation between calcium oxide and calcium phosphate"), while in 2019, distractor selections were spread over three of the four items. Details can be found in Table S2 (Supporting Information Part B). Different item content results in different item difficulties, but the overall trend shows an increase of key selections. This can be seen as a case of

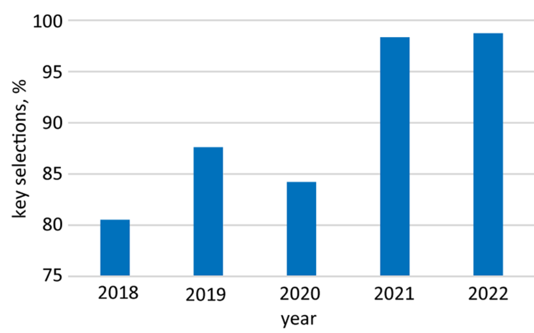


Figure 1. Rates of the key selection of scope questions from exams. See Table S2 (Supporting Information Part B) for details.

identifying a specific teaching objective, which was subsequently addressed by engaging students with appropriate questions for exercises (approximately 20 items in the 2021/22 academic year) and resulted in higher key selections.

■ REVISITING GUIDELINES

During the development and compilation of the question list, it became apparent that some arguably contradict common advice, as they may be trivial, be tricky, or contain irrelevant information. At least in part, this is due to the use as exercises, not exams. In the following, not to reiterate the guidelines for MCQ design,[11,15,25] four themes are revisited.

Trivial Content and Opinion-Based Questions

Opposite to exams, trivial (e.g., easy, a simple case, or with well-known responses) and opinion-based questions can be a good choice during class. For example, questions that may be considered trivial and therefore unsuitable for an exam may be helpful in the classroom or on a worksheet to assess prior knowledge, unveil skill gaps, and reinforce content. Similarly, opinion-based questions are suited for evaluation or to inform contingent teaching,[26] i.e., making further instruction dependent on students' replies. This may also be achieved by asking students about so-called muddiest points.[27,28] Besides, the advantages for requesting students for justifications of *their* responses has been endorsed previously.[22,29−31] Strictly speaking, this is not opinion based but may involve highly individualized reasoning and take clues apart from the subject matter into account.

Tricky but Not Unfair Questions

A common guideline is to "avoid trick questions".[11] Given the ill-defined and potentially misleading term, the author previously refrained from including this in a list.[22] Empirically, the term trick question is associated with a deliberate attempt to deceive.[32] In this sense, all MCQs are trick questions, as the purpose of distractors is to deceive the respondents into the perception that the distractors are the keys. Instead of avoiding trick questions, the author suggests to avoid *unfair* questions but use *tricky* questions. Tricky questions are complex questions which cannot be answered by using the provided material directly and require students to take different aspects into account, which may or may not be mentioned in the question. However, those questions should be *fair* and unbiased, so that skillful and knowledgeable students are able to identify the key (cf. Box 1, questions 2 and 3). While such notions remain circumstantial, the author hopes these are more helpful than "avoid trick questions". This also implies that ambiguity may be intentional. Tricky questions are not meant to be loaded questions, which include false assumptions (example: "How is the absorption of radiation from a hollow cathode lamp by the analyte used for its quantification in ICP-MS?").

Irrelevant Information

Some guidelines advise "avoid irrelevant information".[33] However, students need to be able to evaluate and process the provided information and use it appropriately to solve a problem.[34] This will be undermined if questions are only accompanied by relevant information. Moreover, "irrelevant information" is a vague term because it is not clear whether the information is completely out of context, extraneous,[13] "window-dressing",[11] not useful, or misleading. Questions 2 and 3 (Box 1) are illustrative cases. The relative mass value and isotope abundance mentioned are unnecessary and even misleading, which in turn makes this a tricky question. But, knowledgeable students identify the information as not useful and select the keys.

This does not mean that all or even most questions should contain irrelevant information, but some may be included occasionally. The information should be factual, e.g., contain accurate numerical values, and the wording should not be excessive to allow appropriate processing time.

Correct, Acceptable, and Best Options

MCQs tend to convey the impression that there is a strict dualism between the keys and distractors. Both may not hold up under all circumstances, e.g., because models have a limited scope and instruments work within restricted parameter ranges. A high initial hurdle when first using or developing MCQs may be recognizing that questions are preferably designed for "best" option (also known as one-best-answer question[14] or single best response MCQ[13]) rather than the "correct" option. The author previously mentioned that questions in a "correct-only" mode lack a certain richness (Supporting Information in ref 22), but reasons remained unclear.[22] One aspect could be that they tend to evaluate specific, factual knowledge. Also, the literature mentions the best-option mode as common or advisable,[14] but without further justifying elaborations.

Following Dillon's notion that "A key to understanding what questions are is to understand what answers are.",[35] the author would like to propose a modification: "*A key to MCQ options is to understand what acceptable and unacceptable answers are*." It is by no means the author's intention to negate the notion of correct answers to questions, but for pragmatic reasons, it can be helpful to take "just acceptable" responses into account for the development of MCQs; otherwise, one could easily get bogged down. For example, a meaningful question about appropriate reference materials can be asked of students (Figure 2). As an OEQ without options, there is a wide range of potentially acceptable responses from a generic "with a matrix-matched standard" to a specific "lead in cellulose standard". It is not always straightforward to distinguish between "credit-worthy" (correct and specific) and "credit-unworthy" (correct but generic) responses, even when partial credit can be awarded. To be sure, one then needs to specify in the question what is to be expected, e.g., by extending the question with "Give an example". Asking a MCQ in the best-of mode avoids this by specifying what needs to be evaluated by selecting the key. Figure 2 further provides three different sets of options for the same question. Among the options for question 6a, the generic option (A) is the most acceptable, while the others are unambiguously unacceptable. This mimics a "correct-only" questioning mode and illustrates the aforementioned lack in richness. For question 6b, three options have been changed to specific and generally possible examples and option D becomes in comparison the most unacceptable. Options A and C are very similar (cellulose is a polysaccharide). The question could be given to students as an MCQ with two keys, or one of these options should be deleted or replaced. While option D cannot be considered implausible[36] or outright incorrect, it should be replaced with a more acceptable option. Both aspects are adopted in question 6c. Note that these questions violate the "hand test"[13] or "cover-the-options rule",[14] according to which the key should be inferable from the stem of the question, i.e., without reading the options. This guideline should be considered during question development, but it can be broken

https://doi.org/10.1021/acs.jchemed.3c00061
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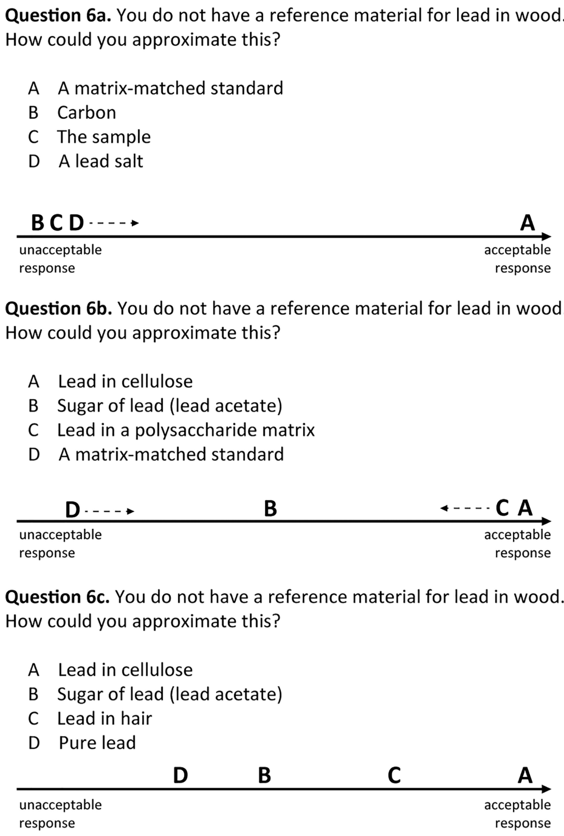

Figure 2. Same question with different options varying in their acceptability as responses. This figure was reproduced with kind permission in an adapted form from ref 37. Copyright 2019 Hogrefe Verlag, Bern.

and still provide a useful question for a class discussion, as this example illustrates.

If nothing else, asking questions in a best-of mode is a pragmatic approach. It helps to avoid lengthy text within the stem or the options in order to separate the key unambiguously from the distractors, as "best" does not mean more elaborate. Furthermore, not providing the "very best" response as an option may introduce useful ambiguity and bypass generic or common replies in OEQs. For questions 4 and 5 (Box 1), replies like "diluted acid" and "extraction" could be considered as the "very best" replies, respectively, but were not listed among the options. Not listing these options reduces the appeal of acceptable responses, and students are required to weigh the options more carefully, while the keys remain unambiguously the best choices. In a similar manner, certain responses may be excluded for essay-like tasks, e.g., "[...] *Select a suitable instrument. An ICP-MS is not available for this analysis.*" The best option mode for MCQs makes it impossible to have more than one or no acceptable option. In such cases, multiple true-false format maybe used instead.

To avoid confusion, it should be noted that Haladyna refers to the "best-answer format" for MCQs whereas *all* options are correct but one is the best,[38] which is not necessarily the case here.

■ GENERATING DISTRACTORS FROM SHORT-ANSWER QUESTIONS

A frequent suggestion is to base distractors on responses to open-ended or short-answer questions,[8,10,39−41] which is also used for research.[42−44] It is however unclear if routine teaching, i.e., in small to midsized courses with a limited number of constructed student responses and only basic coding procedures, would yield sufficient information for plausible distractors. In the Supporting Information Part B, such a tactic is described and its feasibility explored with worksheets in a midsized undergraduate course in analytical chemistry (Figure 3). Please find associated details also in Supporting Information Part B.

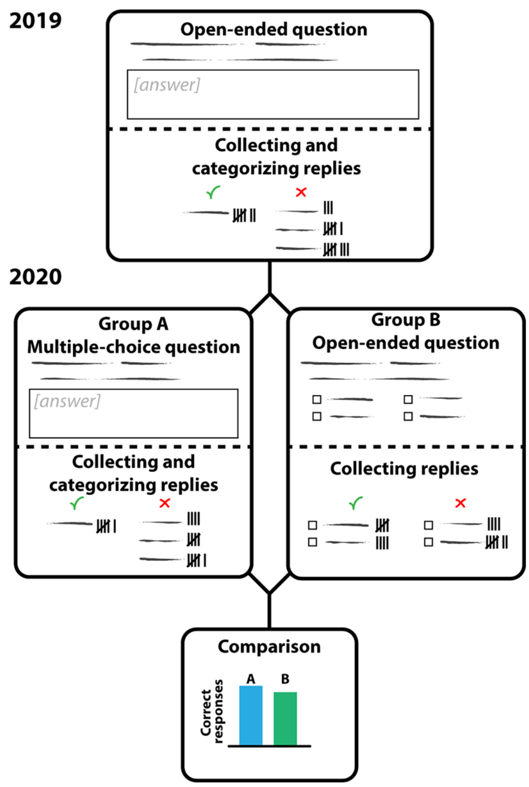

Figure 3. Investigating the development of effective distractors. Replies to the OEQs were collected and categorized, from which distractors were derived. In the subsequent year, the same questions were put as either a MCQ or an OEQ to two groups of students, and response rates compared.

The rates of acceptable responses and key selections were surprisingly similar (Figure 4). It is worth mentioning that none of the open-ended responses to question 17 were acceptable, while it appears that the distractors were so plausible that the key to MCQ 22 was not selected once. A paired samples t test was performed to compare the two question modes. There was no significant difference between multiple-choice (M = 59.0, SD = 26.2) and short answers (M = 59.7, SD = 22.2); $t(42) = -0.09$, p = 0.93).

Overall, this demonstrates that this approach is feasible and provides an encouraging path to develop suitable distractors for MCQs for in-class and out-of-class exercises. This may not result in valid diagnostic items but provides a convenient path suitable for exercises.

■ DISCUSSION

Questions are a necessary part of all active learning approaches, which have gained much attention and momentum in both education research and practice. Still, this has not been followed by an appreciation and study of questioning techniques,

https://doi.org/10.1021/acs.jchemed.3c00061
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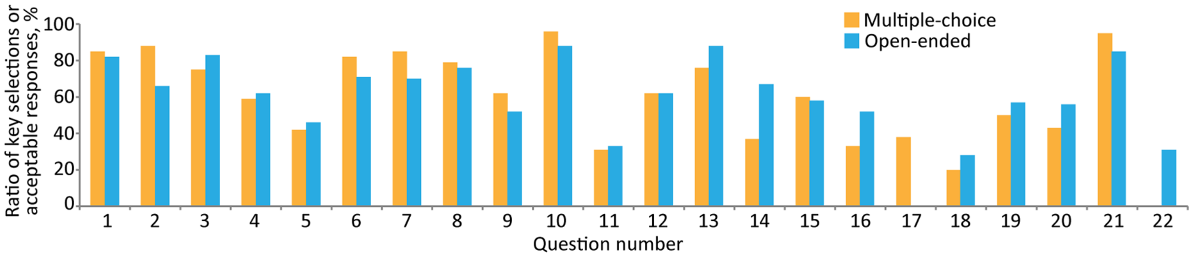

Figure 4. Ratio of acceptable responses or key selections to questions given to students as either MCQs or OEQs. Two questions were omitted due to inadvertently ambiguous options. The number of acceptable responses or key selections to MCQ 22 and OEQ 17 were both zero. Options for two-sided (true/false or yes/no) questions included different justifications, with the exception of question 5.

especially within the contexts of active learning, which is evident in their scarce mentioning and missing question examples in the literature.[5,45] Though, recent examples to the contrary are encouraging.[46−48]

Finding new questions remains a creative and challenging procedure. Many questions, keys, and distractors provided in Supporting Information Part A were based on intuition and experience from years of correcting exams, worksheets, lab reports, and informal discussions with students and colleagues. Nevertheless, mechanisms or tangible models for creating new learning support (multiple-choice) questions remain largely unproductive for developing questions, e.g., for CRSs. Broader and effective adoption of active learning interventions cannot be expected unless more questions are available. The author always found it much easier to modify existing question sets to adapt them to the course and specific lessons than design them from scratch, and he hopes the accompanying list will help others in this regard. Future guidelines should also appreciate exercise material and should be accompanied by related studies.

The scope of the MCQs presented here is limited to quantitative instrumental element analysis as taught in a particular course; e.g., aspects of electrochemical methods were not included. The distractors may not be as effective under other conditions. Still, these questions have the potential to support and inspire other instructors.

Because MCQs do not require students to construct replies, they should be amended with OEQs. Schneider and Preckel emphasized that OEQs are generally preferable and associated with higher achievements in higher education.[4] Nevertheless, MCQs are convenient and suitable for different scenarios, e.g., a section within a written exam. Opposite to OEQs, MCQs can readily be used within mid- to large-enrollment lectures or seminar settings, involving most if not all participants, and receive swift replies.[6,49]

It is important to keep short-answer and essay questions to support related skills, in phrasing responses, and monitor (changes in) student's free responses, e.g., a different focus, new or previously unrecognized potential misconceptions. A suitable balance (e.g., containing trivial, tricky, easy, and complex MCQs and OEQs) needs to be found to effectively and efficiently promote the learning progress.

CONCLUDING REMARKS

Whether for exams or for the practice of skills, developing questions is often tedious. Previous guidelines provide handy clues to avoid pitfalls and meet formal criteria but no concrete subject-specific assistance. The goal should not be to ask as many questions as possible but to ask many learning-supporting questions. This paper provides a substantial number of MCQs for instrumental element analysis and revisits guidelines for development of MCQs for exercises. This results in an increased need to consider MCQs in exercise formats, adapt guidelines, and conduct further studies. Moreover, this communication demonstrates the potential for formulating MCQ distractors from responses to OEQs during routine instruction and introduces scope questions. Mechanisms and models for developing new questions are still needed.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00061.

Part A: Compilation of single choice and multiple true-false questions (PDF; DOCX)

Part B: Multiple-choice question types, details to Figure 1, course and worksheet descriptions; details to generating distractor from short-answer questions (PDF; DOCX)

AUTHOR INFORMATION

Corresponding Author

Gunnar Schwarz − *Laboratory of Inorganic Chemistry, Department of Chemistry and Applied Biosciences, ETH Zurich, 8093 Zürich, Switzerland;* orcid.org/0000-0003-4449-7672; Email: schwarz@inorg.chem.ethz.ch

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.3c00061

Notes

The author declares no competing financial interest.

ACKNOWLEDGMENTS

As the question development is an inherently creative procedure and the list of questions presented here grew over the span of several years, it is hardly possible to relate single items to inspirations by people, specific textbooks, or journal papers. So, the author would first like to thank all those involved. In addition, Alexander Gundlach-Graham, Bodo Hattendorf, Jovana Kocic, Christoph Neff, Guanghui Niu, and Chung-Che Wu and especially Pascal Becker, Chiara Fabbretti, Detlef Günther, Monique Kuonen, the editor, and four anonymous reviewers are gratefully acknowledged for feedback, discussions, and comments to the manuscript.

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NOTE ADDED AFTER ASAP PUBLICATION

Originally published ASAP September 7, 2023; Supporting Information links updated September 8, 2023.

https://doi.org/10.1021/acs.jchemed.3c00061
J. Chem. Educ. 2023, 100, 4099−4105