An Organization Device for Visualizing Mechanisms and Regiochemistry Rationales in Electrophilic Aromatic Substitution

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Abstract: Design and testing of a hand-held device, consisting of two sheets of card stock, presenting electrophilic aromatic substitution (EAS) data in an organized fashion, and designed to facilitate learning electrophilic aromatic substitution reactions is reported. The device includes a large amount of information with similar data grouped, and the groups are juxtaposed in order to facilitate pattern recognition and differentiation. This, in turn, facilitates visualization, retention, understanding, and use of the data presented. One sheet is placed over the other in order to visualize the mechanism between the substituted aromatic compound selected and the chosen reagent. It shows two aspects of EAS on separate pages and, then, demonstrates interactively how they interrelate. The two aspects are (1) the substitution itself, including the identity of the electrophile, the reagent(s) needed to generate it, and the substituent in the product and (2) the electronic effects of the groups in the aromatic compounds upon the intermediate(s) and the structure of the product. The effect of the use of the Electrophilic Aromatic Substitution Tool (also known as EAS-at-a-Glance) on the test performance of students enrolled in undergraduate organic chemistry was determined by a post-test-only control-group study. The subject samples were assigned to a control group and three device groups, differing with respect to use of the device. Results show that the EAS Tool enabled a better student performance (by 12.3% to 17.3%, depending upon the method of use), and that the best method of use is as an out-of-class supplement.

Introduction

The learning of organic chemistry requires understanding a large number of ionic reactions, and electrophilic aromatic substitution (EAS) reactions constitute a large group of reactions in that category. The presentation of EAS reactions is somewhat more complicated than that of most typical ionic reactions because the effects of the existing substituent(s) on the ring must be considered. In order to make the data manageable, most treatments apply some organization, such as categorizing the reactions with respect to the patterns exhibited in the mechanisms and by the effects of the substituents in the aromatic compounds on the reaction rate and regiochemistry. There are, however, other complicating factors, which must be considered, such as (1) any separate reactions that provide the active reagent, (2) the active site(s) in the reactant, (3) the active site(s) in the reagent, and (4) stabilizing charge delocalization due to electronic effects in the intermediate.

A hand-held organizational device for nucleophiles and electrophiles, the Nucleophile/Electrophile Reaction Guide [1, 2], had been favorably received by students in several organic chemistry classes, but it was impossible to include EAS reactions as an entry in this device because of the multitude of variables in the reactions. Because of the rule-based nature of EAS reactions, it seemed possible to offer a simple presentation of these in a separate hand-held organizational device.

Although responses from the students using the device were quite favorable (see below), it seemed of interest to determine quantitatively the effect of using the device on student performance. Accordingly, we wish to report herein the development and testing of the Electrophilic Aromatic Substitution Tool (or EAS-at-a-Glance).

Comments of Students Using the EAS Tool

"Dr. Nelson's Electrophilic Aromatic Substitution Tool summarizes two chapters of text into 4 pages. It is the only tool of this type that I have been able to find. It is extremely helpful in learning the concepts!"

"The EAS Tool helped me visualize the mechanisms of the reactions."

"The Electrophilic Aromatic Substitution (EAS) Tool plays a key role in the visualization of reactions."

"The Electrophilic Aromatic Substitution Tool provides a fresh representation of the course material. It also simplifies things enormously. Everything you need to know is in the palm of your hand."

"The Electrophilic Aromatic Substitution Tool constructed by Dr. Donna Nelson has facilitated my learning of the reaction pathways concerning aromatic compounds with electrophiles. This learning tool has helped me identify the nucleophiles and predict reactions with certain electrophiles. It was easy to learn the characteristics of these reactions given the condensed form of the information."

Device Design and Construction

A prototype for the EAS Tool was created and used in the classroom and then described at a national ACS meeting [3]. It was compared [4] to a slide rule, because it consists of two surfaces that slide against each other with arrows to align in

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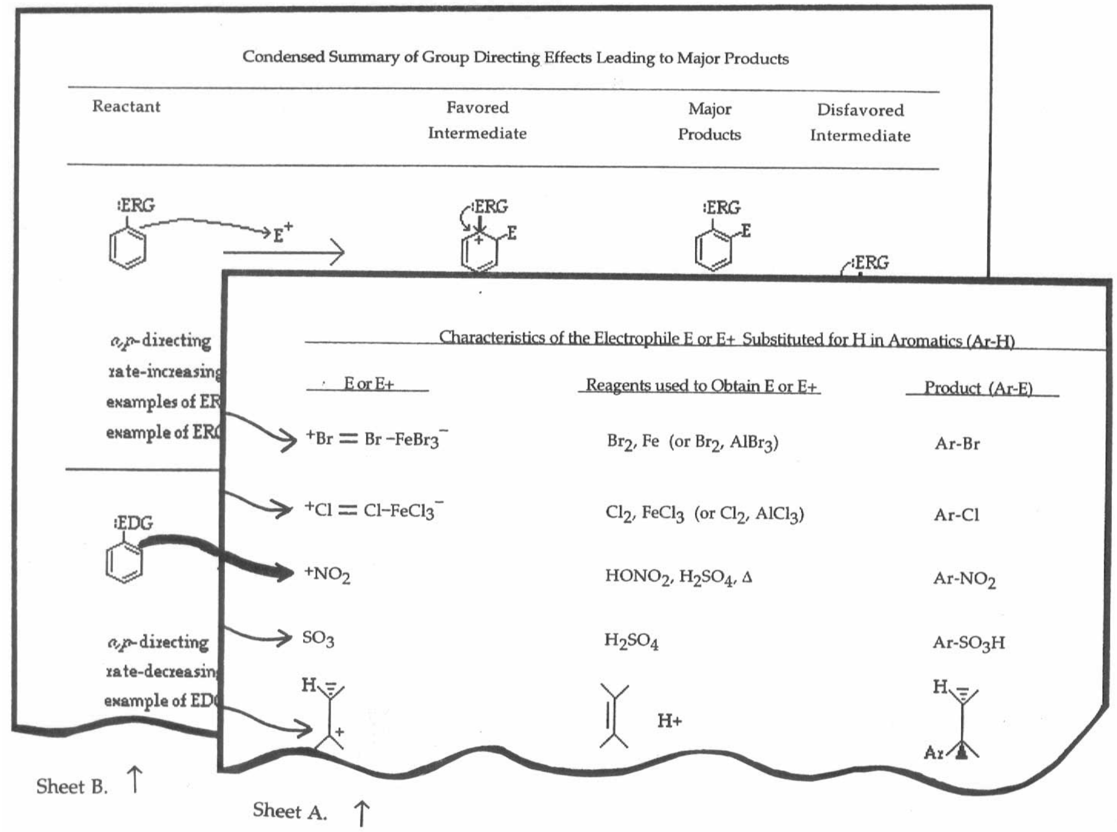

Figure 1. Reduction of a portion of Sheet A of the device placed over two-thirds of Sheet B in order to visualize the mechanism of the rate-determining step of the nitration of chlorobenzene. The arrow halves are juxtaposed in order to show the flow of electrons; the arrow so created in this example is shown in bold type.

order to pair reactants. The device is similar to a slide rule, but different because it also contains a great deal of organized and systematized information. Because of the comparison [4], we received inquiries about the device from universities and businesses, but mostly from industry. Due to apparent interest in the device, we present a description of it and of the application of the organization and systematization techniques to EAS.

The device consists of two sheets of card stock presenting EAS data in an organized fashion to facilitate pattern recognition and retention. One sheet can be placed over the other in order to visualize the mechanism between the substituted aromatic compound selected and the chosen reagent. It gives, on separate pages, two aspects of EAS and then demonstrates interactively how these aspects interrelate. The two aspects are: (1) the substitution itself, including the identity of the electrophile, the reagent(s) needed to generate it, and the substituent introduced in the product and (2) the electronic effects of the groups in the aromatic compounds upon the intermediate(s) and the structure of the product.

Sheet A (Figure 1) has a discussion about and a table of representative electrophiles, the reagents needed to generate them, and the general class of product obtained from the reaction of each electrophile with an aromatic compound. In the first column, the electrophile (E or E+) undergoing attack by the π electrons of the aromatic compound is listed.

Each electrophile in the E or E+ column has the head half of an arrow leading from the side of the page and pointing to an atom that is the reactive site in the electrophile, the atom bearing the highest amount of positive charge or the lowest electron density. This atom is the one that will bond to the aromatic ring. In the second column are the reagents that generate the electrophiles in the first column. The third column lists the product obtained by treating the aromatic compound with the reagent(s) in the second column. An introduction and additional discussion are on the reverse of Sheet A with definitions of the aromatic-ring positions relative to the group in the reactant and an explanation of the four different types of electronic effects caused by substituents in the aromatic reactants. These four different categories of electronic effects are: (1) ERG (π system), which stands for Electron-Releasing Group via the π system; (2) ERG (σ system), which stands for Electron-Releasing Group via the σ system; (3) EDG, which stands for Electron-Delocalized Group; and (4) EWG, which stands for Electron-Withdrawing Group.

Sheet B bears a table consisting of columns of information about group-directing effects in EAS. Information is categorized with respect to the type of electronic effects caused by the substituents in the aromatic reactant; the members and characteristics of each category are placed next to each other to facilitate pattern recognition and thereby retention of the data presented. The first column contains a series of monosubstituted aromatic compounds as reactants categorized according to the type of electronic effects (defined at the bottom of the table) caused by the substituent present. A general description of the type of electronic effect and example substituents are below each substituted aromatic compound. The arrow leading from the reactant molecule to E+ represents

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the electrophilic attack of the π electrons upon the general electrophile (the rate-determining step of the reaction). The second column has the most stable resonance structure(s) of the most-favored intermediate(s) of the reaction with arrows depicting electron withdrawal or donation to justify why that intermediate is disfavored. Because the position of the carbon–electrophile bond has been established by this point, each intermediate leads logically to the major product(s), which are given in the third column. The fourth column shows the disfavored intermediate with arrows depicting electron withdrawal or donation and justifying why that intermediate is disfavored.

In order to consider the reaction of a specific electrophile with a type of aromatic reactant under the effects of its substituent(s), it is necessary to juxtapose Sheet A and Sheet B. Bringing together the two reactants enables one to visualize the mechanism of the rate-determining step of a specific reaction while considering and tracking all of the variables involved. Attack at each specific E or E+ is shown in the far-left column of Sheet A with arrows leading to each from the edge of the card. Attack by the aromatic compound upon a general electrophile, E+, is shown in the left one-third of Sheet B with arrows leading from the aromatic compound to E+. Thus, in order to visualize the rate-determining step of a specific reaction, place Sheet A over the right two-thirds of Sheet B and align the head of the appropriate arrow on Sheet A with the base of the appropriate arrow on Sheet B. The steps involved in this process are: (1) select the aromatic structure bearing the desired group type; (2) locate the corresponding base half of the arrow desired; (3) select the desired reagent(s) to be used or the electrophile provided; (4) determine the corresponding head half of the arrow desired; (5) visualize the mechanism leading to the correct intermediate(s) by placing Sheet A over the right two-thirds of Sheet B and aligning the selected head half-arrow with the selected base half-arrow.

Two examples demonstrating the use of the EAS organization device to visualize the mechanistic attack of the aromatic compound upon the electrophile (E or E+) and leading to the intermediate and product with the proper regiochemistry are given on the reverse of Sheet B in the device.

They are (1) Friedel–Crafts acylation of a halobenzene and (2) chlorination of phenol. The latter example is reproduced in Figure 1.

Measuring the Effect of the Electrophilic Aromatic Substitution Tool

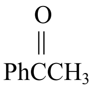
The subject students were enrolled in a second-semester organic chemistry course for science and engineering majors at a comprehensive public university. The sample consisted of 167 students: 93 were assigned to a control group, 26 were assigned to an out-of-class device group, 33 were assigned to an in-class device group, and 15 were assigned to use the device both in class and out of class (Table 1). Assignments were random, and the course met for a total of 150 minutes per week for the 15-week semester. The four different groups were organized according to device use. Group YY saw demonstrations of how to use the device in class, mimicked the use of the device in class, and then used it unsupervised outside of class. Each student in an in-class device group (Group YN) saw the demonstration, mimicked the demonstration with a device, continued to use the device in class, but did not use the device outside class. Each student in the out-of-class device group (Group NY) saw demonstrations of how to use the device in class and then used the device unsupervised outside of class. The students in the control group (Group NN) did not use the tool at all; thus, the uses of the device by Group YY would be a combination of those of the in-class group (Group YN) and of the out-of-class group (Group NY) described above.

The experimental design is a posttest-only control-group design for both content knowledge and problem solving. The questions used in the posttest were

1. What is a major product of the reaction of toluene with $HONO_2/H_2SO_4$?
a. *p*-nitrotoluene
b. *m*-nitrotoluene
c. *p*-toluenesulfonic acid
d. *m*-toluenesulfonic acid

2. What reactant and reagent can be used to accomplish alkylation of aromatic compounds?
a. alkene + H_2SO_4
b. alcohol + H_2SO_4
c. $RCl + AlCl_3$
d. all of the above

3. What is the electrophile that reacts with benzene in the following reaction?
$\text{benzene} \xrightarrow{HONO_2 + H_2SO_4}$
a. NO_3
b. $^{+}NO_2$
c. SO_3
d. $^{+}SO_3H$

4. Which of the following would be most reactive toward ring bromination?

a. $\mathrm{Ph}\overset{\overset{O}{\|}}{\mathrm{C}}\mathrm{CH_3}$
b. $PhCH_3$
c. $PhNH_2$
d. benzene

A Control-Unit Achievement Test [5] (CUAT) showed that the groups were approximately equivalent in their chemical knowledge before the treatment. The CUAT was a test given over a unit of instruction with no content that served as the treatment for the research in organic chemistry.

Before the treatment, students' knowledge in chemistry was tested by using the CUAT. Corrections to the groups' scores on tests measuring the effects of using the EAS Tool were based on differences in the results of the groups of this Control-Unit Achievement Test.

The texts used during this study were *Organic Chemistry*, 3rd ed. and the accompanying study guide by Professor Seyhan Ege. In order to explore the effect of changing texts upon the improvement brought about by using the EAS Tool, the study was repeated the following year using *Organic Chemistry*, 3rd ed. and the accompanying study guide by Professors K. Peter C. Vollhardt and Neil E. Schore. The results were analogous.

Table 1. Data based on student responses about use of the EAS Tool

	Use of Device				
	in and out of class (YY)	in class only (YN)	out of class only (NY)	in and/or out (wt.ave. YY, YN, NY)	none (control) (NN)
Count	26	33	15	74	93
GPA	3.36	3.03	3.00		3.18
CUAT score	62.7	53.6	55.0	56.5	59.6
control score - group score% correct	-3.1	6.0	4.6	3.1	0.0
Q1	92.0	81.8	86.7	85.1	75.3
Q2	60.0	60.6	73.3	62.2	51.6
Q3	96.0	75.7	73.3	81.1	75.3
Q4	84.0	75.7	80.0	78.4	80.6
Ave Q1-Q4	83.0	73.4	78.3	76.7	70.7
average Q1-Q4 w/CUAT correction	79.9	79.4	82.9	79.8	70.7

Results and Discussion

The results from the EAS Tool study are shown in Table 1. The questions used were designed to determine student knowledge of various aspects of the EAS reactions that were included in the tool. The percent correct response for each test question is shown for each of the sample groups, Group YY, YN, NY, and NN (columns 1 through 3 and 5), as well as for a weighted average of all groups using the device in any manner (column 4).

The Control-Unit Achievement Test (CUAT) scores for the groups, the last row of entries in Table 1, indicate that there was little difference between the three treatment groups and the control group: YY, 62.7%; YN, 53.6%; NY, 55.0%; NN, 59.6%. The weighted average for all groups using the device is 66.4%, almost identical to that of the control group. Grade-point averages (GPAs) of the students were collected from student records, and averages of these for the groups are given in Table 1.

The average of the four questions for each group is given in Table 1 (Ave Q1–Q4). The results are as follows: Group YY, 83.0%; Group YN, 73.4%, Group NY, 78.3%, Group NN, 70.7%. All three of the groups that used the Reaction Guide (Groups YY, YN, and NY) performed significantly better than those of the control group (Group NN), and the weighted average of all groups using the device is 76.7%. Curiously, of the three groups using the device, the group that used the device both in and out of class scored marginally lower than the other two. The control group had the lowest average score on every test question except one (Question 3), and for that question it had the next to lowest score.

If the average results (Ave Q1–Q4) are normalized using factors obtained from the CUAT scores (control score - group score), the corrected averages (corrected average Q1–Q4) become Group YY, 79.9%; Group YN, 79.4%, Group NY, 82.9%, Group NN, 70.7%. This analysis of the results shows that Group NY shows improvement that was greater by 12.3% (compared to YN) to 17.3% (compared to the control NN) as a result of using the EAS Tool. However, use of the device outside of class in addition to using it in class gives only a small improvement, as learned by comparing groups YY (79.9%) and YN (79.4%). The differences in the GPAs of the groups of students are small to negligible, but it is interesting to note that the group with the lowest GPA, Group NY, benefited the most from the use of the device.

The value of tables to organize data and infer patterns in teaching organic chemistry is well-established. Student learning from these tables might take the form of three different levels of mastery. (1) Students may simply memorize the table with little understanding of the concepts behind it. This is the lowest level of mastery. (2) In an intermediate level of mastery, the students may begin to recognize patterns, but not understand the origin of these patterns. (3) The highest level of mastery is reached when the student has a full grasp of the basic conceptual fundamentals of the topic and is capable of applying these ideas to situations that are totally new to the student. A class handout, textbook table, or any other pedagogical organizational tool must be designed to encourage conceptual learning, perhaps through exploring patterns or reactivity. This tool does that [6], but the major difference between this tool and a simple organizational table or handout is that it demonstrates, by visualization and by moving the two pages positioned against each other, that all permutations of (1) substituent in the aromatic compound, (2) position of substituent in the aromatic compound, and (3) electrophile are allowed.

Conclusion

The design group had significantly higher scores than the control group on the posttest. The control group had the lowest average score on every test question except one, and for that question it had the next to lowest score. This indicates that the Electrophilc Aromatic Substitution Tool improved student performance in this undergraduate organic chemistry class. Data from the performance of the design groups and information from a subsequent questionnaire indicate that the best method of use of this device for most students is probably as an out-of-class supplement.

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References and Notes

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6. Much of the preceding information and phraseology in this paragraph came from a referee of this manuscript, whose comments are greatly appreciated.

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