

A Single Reaction Thread Ties Multiple Core Concepts in an Introductory Chemistry Course

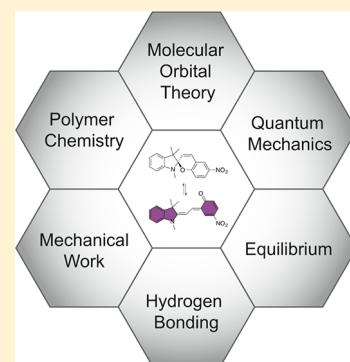
Meredith H. Barbee,[†] Robert G. Carden,[†] Julia H. R. Johnson, Cameron L. Brown,[‡] Dorian A. Canelas,^{*} and Stephen L. Craig^{*‡}

Department of Chemistry, Duke University, Durham, North Carolina 27708, United States

S Supporting Information

ABSTRACT: This work describes the use of a single chemical reaction to teach and connect a number of standard general chemistry course topics while also introducing students to polymer concepts. Through the study of the reaction that converts spiropyran into merocyanine, we are able to present and connect molecular orbital theory, quantum mechanics, equilibrium, hydrogen bonding, mechanical work, and polymer chemistry. By framing a number of different concepts with the same reaction, our goal is to allow students to see connections in seemingly disparate sections of general chemistry. At the same time, repeated study of this organic reaction provides a pathway for students to gain confidence and comfort with carbon-based molecular structures before stepping into an organic chemistry course. Experimental results indicate that there is no significant difference in student performance on problems linked to unit learning objectives when a group of students who complete the spiropyran-based exercises is compared to a control group who completed exercises involving smaller molecules. We describe here the materials used in both a team-based learning classroom and a concurrent laboratory module.

KEYWORDS: Inquiry-Based/Discovery Learning, Polymer Chemistry, First-Year Undergraduate/General, Student-Centered Learning, Hands-On-Learning/Manipulatives



INTRODUCTION

Recent revisions to the guidelines from the American Chemical Society Committee on Professional Training (ACS-CPT) have sparked interest in innovative approaches to the structure of foundation-level chemistry courses.¹ In particular, calls have been made to rethink chemical education in the context of an increasingly interdisciplinary world.¹ Additionally, specific recommendations have recently been made to include polymer chemistry content in the introductory sequence,² as the field is often overlooked or underrepresented in undergraduate general chemistry, despite the fact that roughly 50% of all chemists work with polymers at some point in their careers.³ Some have called for a complete redesign of the chemistry curriculum in an attempt to integrate the traditional domains of chemistry, effectively eliminating courses in discrete disciplines and replacing them with basic, intermediate, or advanced chemistry.⁴ Courses in synthesis, analysis, or theory development have been proposed to better prepare students for future careers;⁵ however, because many departments might be reluctant to restructure the chemistry curriculum, others suggest modifying traditional courses so that they are more integrated.⁶ Historically, a standard general chemistry course attempts to introduce students to this integrated network of chemical sciences by discussing seemingly disconnected topics such as chemical equilibria, molecular orbital theory, and the thermodynamics associated with work throughout a semester. Here, we describe efforts to improve our general chemistry course by framing the content of multiple units and a

laboratory around a single reaction from organic chemistry. The structure of this series of exercises takes advantage of the associative learning principle⁷ to draw connections between diverse topics in general chemistry (molecular orbital theory, quantum mechanics, equilibrium, hydrogen bonding, mechanical work, and polymer chemistry).

Our choice of organic chemical reaction is the interconversion of spiropyran (SP) to the highly colored and fluorescent merocyanine (MC), a reaction that occurs in response to changes in solvent or various thermal, photochemical, or mechanochemical stimuli (Figure 1).⁸ The chromic nature of this reaction provides an extremely versatile framework through which to integrate and move between a wide array of topics typically covered in a general chemistry course. Many colleges in the United States have transitioned to a 1–2–1 introductory course sequence,⁹ with a single, college-level general chemistry course, then two organic chemistry courses, then a second general chemistry course. Due to this change in structure, the choice to employ an organic molecule to illustrate concepts in the context of a general chemistry setting provides learners with an opportunity to become familiar with working with carbon-based molecular structure and properties before transitioning into an organic chemistry classroom. The SP-to-MC conversion also involves a substantial change in molecular shape, providing

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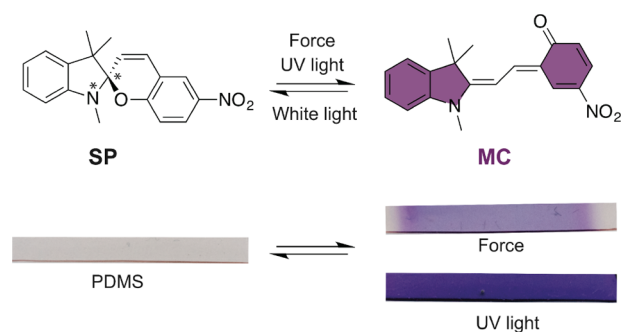


Figure 1. Spiropyran (SP) undergoes a ring-opening reaction to give the highly colored and fluorescent merocyanine (MC) in response to photochemical or mechanochemical stimuli. Appropriate derivatives of SP can be chemically cross-linked into a silicone (polydimethylsiloxane), PDMS) network, and the resulting effects of mechanical force and UV light on the material can be observed.

75 an accessible and valuable entry point into the practice of
 76 molecular visualization, a common barrier for success in organic
 77 chemistry.¹⁰ Furthermore, because SP has been developed by
 78 Moore, Sottos, and White as a signature mechanophore
 79 (mechanically active functional unit)^{8b} in the nascent field of
 80 polymer mechanochemistry,¹¹ it functions as a bridge between
 81 the concepts of classical thermodynamics/chemical kinetics and
 82 polymer chemistry by demonstrating the direct coupling of
 83 mechanical work and chemical potential. Ongoing research
 84 with SP in the Craig lab^{8c,12} inspired the development of this
 85 exercise as a way to gently encourage first-year undergraduate
 86 knowledge of and curiosity about local research opportunities.
 87 Finally, the use of a reaction that has a visible output allows
 88 facile integration into the complementary laboratory portion of
 89 the course; this has been shown to increase student investment
 90 and understanding of the material.¹³ We have implemented the
 91 sequence of activities described here in the context of a team-
 92 based learning (TBL) classroom, but it is similarly well-suited
 93 to a traditional lecture and/or hybrid classroom models. To test
 94 the efficacy of these newly developed spiropyran-based
 95 applications, we assessed student demonstration of mastery of
 96 the course learning objectives that are central to these
 97 applications in comparison to a control group who performed
 98 more traditional applications centered on the same learning
 99 objectives.

100 Herein we (1) report information about the course structure
 101 through which these spiropyran applications were first
 102 implemented, (2) describe the spiropyran-based classroom
 103 module and lab, and (3) present experimental results from a
 104 classroom-based study that compared the SP-based approach to
 105 a different, more traditional inorganic approach to obtaining the
 106 same general desired learning outcomes.

107 ■ COURSE STRUCTURE

108 The course for which this material was initially designed was
 109 taught in an interactive, cooperative classroom structure. Each
 110 year this class is composed of 100–120 students, the vast
 111 majority (>98%) of whom are first-semester undergraduates. At
 112 our university, first-year students place into their initial
 113 chemistry course based upon a combination of high school
 114 chemistry experience, math SAT scores, and chemistry AP
 115 scores. There are 4 different classes that students can place
 116 into:¹⁴ an introductory class which assumes no prior back-
 117 ground in chemistry,¹⁵ the first semester of a traditional 2-

semester general chemistry sequence, an organic chemistry 118
 class (AP score of 5, or equivalent, is required for this initial 119
 placement), and the course described here. This course is called 120
 “Honors Chemistry”, and it is a one-semester version of general 121
 chemistry for students who have completed AP chemistry and 122
 scored either a 4 or 5 on the AP exam. We employ a team- 123
 based learning (TBL)¹⁶ classroom model, in which the students 124
 work together in teams of 4–6 members for the entire 125
 semester. In line with previous studies,¹⁶ we have found that 126
 keeping teams intact throughout the semester increases the 127
 students’ trust in each other and allows for the development of 128
 a positive group dynamic. 129

Class periods are twice per week for 1 h and 15 min. Digital 130
 course materials, organized in terms of the learning objectives 131
 for each unit and accompanied by self-assessment exercises, are 132
 provided at the start of the semester via an online course 133
 management site; there is no required textbook for the course. 134
 All students also participate in an accompanying laboratory 135
 section that meets once per week for 3 h; the laboratory score is 136
 incorporated as part of the overall score used to determine 137
 course letter grades. In addition, an optional class meeting 138
 period is available each week prior to the start of each unit and 139
 again midway through the longer units. At this optional 140
 “discussion” meeting (formerly called recitation), questions 141
 regarding the core learning objectives or assigned homework 142
 problems can be discussed with the instructor or course 143
 teaching assistants, and the concepts associated with the online 144
 problems most frequently answered incorrectly by students in 145
 the course are clarified. 146

The semester-long course is divided into 8 units; a 147
 description of the units, and the order in which they are 148
 presented, is provided in Table 1. Each unit follows the same 149

Table 1. Course Structure

Unit and Topics	Dedicated Class Periods
Unit 1: Energy, Enthalpy, Thermochemistry	2
Unit 2: Atomic Electronic Structure	2
Unit 3: Molecular Structure	3
Unit 4: Molecular Orbital Theory	4
Unit 5: Chemical Equilibrium	2
Unit 6: Entropy and Free Energy	2
Unit 7: Acids and Bases	3
Unit 8: Kinetics and Catalysis	4

150 pattern: students are expected to use the unit plans with online
 151 materials, graded online homework, and the optional class
 152 discussion period to learn or review basic concepts at their own
 153 pace prior to the class meeting, and then the first required class
 154 period on the unit begins with an ~20 min 10 question
 155 multiple choice Individual Readiness Assurance Test (IRAT).
 156 This is immediately followed by a team discussion of the same
 157 problems and Team Readiness Assurance Test (TRAT). The
 158 TRAT allows students to take the IRAT as a group using
 159 Immediate Feedback-Assessment Techniques (IF-AT) scratch
 160 cards so that all students finish the team exercises with full
 161 awareness of the correct answers.

162 Following the TRAT, the remainder of the unit (1.5–3.5
 163 class periods) is spent on application problems that are worked
 164 by the teams as the instructor and teaching assistants (TAs)
 165 circulate in the room. There are periodic opportunities for
 166 reporting answers and class-wide discussion and brainstorming,
 167 but most of the class time is spent with the students working in

168 their small teams. It is within the context of these team-based
 169 application problems that the activities reported and discussed
 170 here are employed. These application problems and RATS are
 171 available in the [Supporting Information](#). Other course unit
 172 exercises are available upon request.

173 ■ SPIROPYRAN APPLICATION ACTIVITIES

174 In the structure of the semester, we introduce the reversible
 175 structural transformation between SP and MC during Unit 4:
 176 Molecular Orbital Theory. This chemical reaction is introduced
 177 through a demonstration with an accompanying team
 178 application problem worksheet (see [Supporting Information](#))
 179 that shows the molecular structures of both SP and MC. First,
 180 the students are shown a clear, colorless solution of
 181 commercially available SP in toluene. Then, the solution is
 182 irradiated with a blue LED light, and during this perturbation,
 183 the solution briefly turns a deep blue/purple. Students are told
 184 that the MC compound's structure gives rise to this color. In an
 185 application problem completed by the teams during class, the
 186 students are first asked to consider the reaction in the context
 187 of molecular shape: the teams are asked to explain the
 188 relationship between the change in hybridization of the central
 189 carbon atom and the ensuing change in the geometry of the
 190 molecule. The questions asked in the application rapidly segue
 191 into a discussion of the importance that conjugation has on
 192 extended molecular geometry and the color change of the
 193 reaction, including using the particle-in-a-box model to connect
 194 the Schrödinger equation to the energy gap between electronic
 195 energy levels and associated color change. Concurrently during
 196 the weeks of these in-class discussions, students conduct a
 197 laboratory experiment focused on probing the chemical
 198 equilibrium, solvatochromism, and impact of solution polarity
 199 and hydrogen bonding on the equilibrium of the SP-to-MC
 200 conversion, which leads into Unit 5: Chemical Equilibrium.

201 We finish our discussion of the SP/MC reaction by tying it to
 202 mechanical work through a hands-on activity that illustrates the
 203 ability to physically pull on the sides of the molecule embedded
 204 in a polymer film and force the opening of the ring. This
 205 provides an opportunity to revisit concepts from the first unit in
 206 the course (Energy, Enthalpy, and Thermochemistry), but in a
 207 very visual context of a chemical reaction system, as opposed to
 208 the compression and expansion of ideal gases. More specifically,
 209 polydimethylsiloxane (PDMS) films with mechanochemically
 210 active SP are shown to the class, and some students are given
 211 small samples to manipulate and share with their teams. The
 212 films change color either by pulling on the ends of the film in a
 213 stretching deformation or upon UV irradiation ([Figure 1](#)).
 214 Generally, two class periods are spent working on the SP-to-
 215 MC module. The experimental details of the demonstration,
 216 the application problem, and the lab exercise can be found in
 217 the [Supporting Information](#).

218 ■ LEARNING OBJECTIVES

219 The utility of the SP-to-MC module is that it ties together a
 220 wide range of learning objectives (LOs). The LOs for the
 221 course, organized by unit, are provided in the [Supporting](#)
 222 [Information](#), with the specific LOs addressed in this module
 223 highlighted for reference. The LOs that were assessed in a
 224 postactivity pop quiz focused on molecular orbital theory,
 225 quantum mechanics, equilibrium, hydrogen bonding, work, and
 226 polymer chemistry.

Molecular Orbital Theory

227

Novice students often initially identify conjugated bonds as a
 double bond–single bond–double bond pattern from observ-
 ing presented example structures without fully grasping the
 aspects of the molecule that make a conjugated system. The SP-
 to-MC reaction allows the instructor to emphasize the
 molecular orbital features that make a molecule conjugated.
 When discussing this problem, we first ask the students to
 consider the geometry and hybridization of each of the atoms
 in the structures of both SP ([Figure 2](#)) and MC ([Figure 2A](#)).
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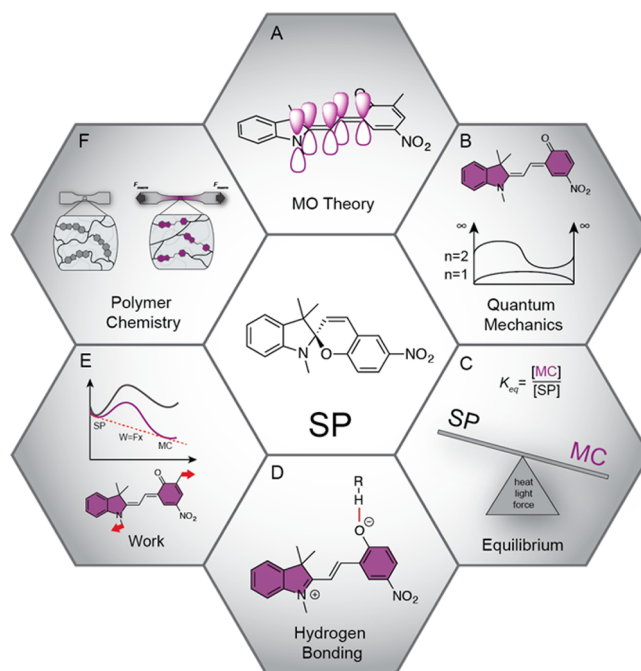


Figure 2. New applications are structured around a single reaction from organic chemistry to connect diverse topics in general chemistry (MO Theory, Quantum Mechanics, Chemical Equilibrium, Hydrogen Bonding, Chemical Work, and Polymer Chemistry). The red arrows in part E represent the pulling points where the molecule is covalently bound into the polymer network.

Next, learners are asked to identify geometry and hybridization
 changes that occur as a result of the breaking of the C–O
 spirocycle bond. As part of this in-class assignment, students are
 informed that the geometry about N1, denoted by * in [Figure](#)
 1, in SP is trigonal planar, and they are asked to classify the
 hybridization of the N and the surrounding atoms. The student
 teams quickly identify that only the central carbon, C1, denoted
 by * in [Figure 1](#), changes hybridization during the trans-
 formation between the two molecules. Indeed, C1 changes
 from sp^3 hybridization in SP to sp^2 hybridization in MC. It is
 helpful for the students to visualize the three-dimensional
 geometry and associated atomic orbitals surrounding the C1 in
 these two configurations. We find that molecular modeling
 software, if available, can facilitate this visualization (our
 students use Spartan Student).¹⁷ Students are encouraged to
 build the compound on the computer outside of class to
 prepare for the application problem; this could also be done in
 the lab during the week prior to the application. We find it
 instructive to emphasize that this local change in hybridization
 (rupture of a single bond and rehybridization of a single atom)
 brings about a global change in molecular structure; the right-

258 most side of the MC becomes coplanar with the left-most side,
259 because of conjugation that is continuous across the molecule.
260 The key point is that the change to sp^2 hybridization provides
261 an unhybridized p orbital that can connect two conjugated π
262 systems that are initially separated on either side of the
263 spirocycle connection, a very dramatic consequence of
264 delocalized, molecular orbitals that cannot be explained by
265 localized bonding models such as valence shell electron pair
266 repulsion.

267 Quantum Mechanics

268 The change in conjugation provides a smooth transition into a
269 tangible application of the Schrödinger equation and its
270 relationship to color and conjugation (Figure 2B). After
271 highlighting and discussing the concepts of hybridization and
272 conjugation in the SP and MC molecules, the students are
273 challenged to explain why SP is colorless and MC exhibits a
274 purple color. They are prompted specifically to invoke the
275 particle-in-a box model during their explanation. The key
276 connections include the following: first, that the color of the
277 molecules relates to whether or not they absorb light in the
278 visible spectrum; second, that the wavelengths absorbed
279 correspond to energies of associated electronic transitions
280 (longer wavelengths means smaller HOMO–LUMO gap);
281 third, that the spacing between orbital energies decreases as the
282 size of the box increases in the particle-in-a-box model; and,
283 fourth, that the size of the “box” corresponds not to the size of
284 the molecule, but to the size of the conjugated π system in the
285 molecule.

286 The consequence of increased conjugation in MC is
287 therefore that the gap between the orbital energy levels in
288 MC is smaller than in SP, and less energy is needed to promote
289 an electron to the excited state of MC than is required for SP.
290 This lower energy corresponds to a longer wavelength in the
291 MC molecule (absorbance in the visible) when compared to SP
292 (absorbance almost entirely in the UV).

293 Equilibrium and Hydrogen Bonding

294 Through this exercise, students are also challenged to connect
295 molecular structure and resonance to polarity. The teams are
296 tasked with drawing two resonance structures for MC, one of
297 which has formal charge on the nitrogen in the ring structure
298 and one of which does not. They are then asked to consider the
299 resonance structures and predict the polarity of MC relative to
300 SP. Having identified that MC is more polar because of the
301 additional charge separation found in one resonance structure,
302 they are then asked to predict how solvent polarity will
303 influence the amount of MC relative to SP at equilibrium.

304 The groups determine that, due to it being a more polar
305 molecule with greater charge separation, MC will be stabilized
306 in more polar solvents (Figure 2C). This provides the
307 foundation for a subsequent laboratory exercise, in which
308 students are provided a solution of SP in toluene and given a
309 set of cosolvents (methanol, ethanol, acetonitrile, acetone, and
310 THF) to add. They are given the dielectric constant of each
311 solvent and the dipole moment of each solvent molecule, and
312 then they are asked to predict which cosolvent will result in the
313 greatest conversion of SP to MC, and hence have the greatest
314 color change. Invariably, students predict that because it has the
315 highest dielectric constant, acetonitrile will generate the greatest
316 color change. Different lab groups add different amounts of the
317 various cosolvents and record the changes in absorbance at 540
318 nm. The results of all lab groups are compiled and presented in
319 class (representative data shown in Figure 3), verifying what

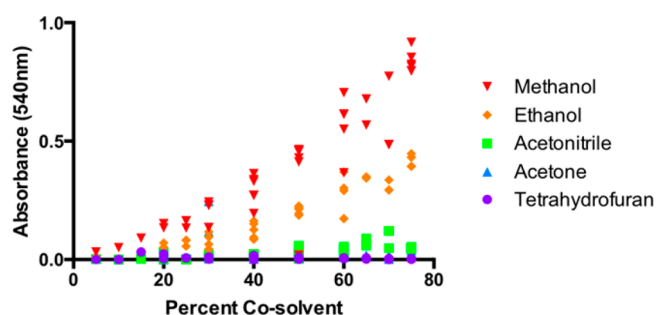


Figure 3. Representative student data for a plot of absorbance (540 nm) of the SP-to-MC conversion vs percent cosolvent added to a solution of SP in toluene.

most groups concluded from their own observations: despite
having lower dielectric constants than other cosolvents,
methanol and ethanol are the most effective cosolvents at
shifting the SP/MC equilibrium toward MC.

When asked about this in class, a few students will have
speculated (correctly) that the reason is hydrogen bonding,
a concept familiar to them from high school, but also presented
by the conversion of SP to MC is a strong hydrogen bond
acceptor, as shown in Figure 2D. Some students will
hypothesize that the lone pairs of electrons on the oxygen
positive charge that develops on N1 in MC, providing an
opportunity to discuss THF as a control that contradicts that
hypothesis. The demonstration highlights in a visible manner
the importance of hydrogen bonding as a strong intermolecular
force in determining molecular behavior by providing the
energy required to “pull” SP sufficiently to convert it into MC.

Work and Polymer Mechanochemistry

To this point, students have seen how the energy necessary to
convert SP to MC can be provided by light and by solvation
interactions, particularly hydrogen bonding. We conclude the
module by demonstrating how mechanical work can similarly
provide the necessary energy input for the transformation. The
specific mechanism of doing work on the system is polymer
mechanochemistry, in which the work is delivered by applying a
force across a distance (change in molecular length) as opposed
to pressure across a change in volume (Figure 2E).^{11a} We find
this to be a compelling and captivating example of work for a
chemistry course, as it involves actual chemical change, the
paradigmatic conversion of SP to MC. Since mechanical force is
generally applied to the mechanophore via polymer “handles”,
this provides a natural segue into a more general discussion of
polymer chemistry. We begin by pointing out that it is
effectively impossible to use our human hands to hold the
carbon and oxygen atoms in the scissile bond. So, to apply a
force directly to the SP, we need to form a covalent bond
between the SP and something that is large enough to hold
with our fingers.

The mechanism for accomplishing this that the instructor
describes is to form bonds between SP and a chemically cross-
linked PDMS elastomer (Figure 2F).^{8c} This provides an
opportunity to discuss the molecular structure of polymers and
cross-linked polymer networks, including the fact that a piece of
a cross-linked rubber is largely a single molecule. For our class,
we bring in strips of PDMS film into which SP has been
appropriately cross-linked, using a simple formulation that can

367 be repurposed effectively for outreach demonstrations.¹⁸ We
368 prompt the class to vote as to whether or not a person is strong
369 enough to break a chemical bond (in our experience, most
370 students think not). Then, the instructor describes the film
371 composition and invites volunteers to come forward to stretch
372 the films with their fingers. Upon stretching, the film changes
373 color as a result of the mechanical work being channeled
374 directly into the SP-to-MC conversion. In the context of
375 polymer education, this demonstration drives home the point
376 that polymers are made up of molecules, and that the behavior
377 of the material is intrinsically coupled to the behavior and
378 properties of the molecular constituents.

379 After demonstrating how the work done by a person's fingers
380 can convert the colorless polymer to purple, we discuss how
381 one would choose which bonds in SP to replace with bonds to
382 the polymer. There are two considerations. First, the
383 substitution must not disrupt the conjugation in the MC, and
384 so replacing a σ bond (for example, to a hydrogen atom) that is
385 outside the conjugated π system is discussed as the best
386 strategy. Second, the chosen positions must couple to the ring-
387 opening reaction (that is, they must move away from each
388 other after the C–O bond breaks). Because work is force \times
389 distance, the further the substitution positions move away from
390 each other, the less force is required to provide the necessary
391 work. If available, using a computer modeling program to
392 determine the distance between points and calculating the force
393 needed to break the bond gives students an early opportunity
394 to attempt molecular visualization, for some students, a barrier
395 to success in subsequent organic chemistry courses.¹⁰
396 Molecular model kits could be used to aid in visualization as
397 well.

398 This exercise ties a chemical reaction to the seemingly
399 abstract physical concepts of work and its relationship to
400 internal energy (these were covered in the first unit of the
401 course). It also allows for a discussion of what a polymer is and
402 how polymers can have molecular functionality embedded
403 within them for desired chemical effects.

404 Extension to Organic Chemistry Courses

405 Although we use the SP-to-MC module in an accelerated
406 general chemistry course, we recognize that not all universities
407 have an equivalent course. We think this module could easily be
408 adapted to an organic chemistry setting. In fact, many of the
409 concepts presented in this general chemistry module are often
410 covered in the introductory chapters of an organic chemistry
411 textbook.¹⁹ The details are beyond the scope of this paper, but
412 the SP-to-MC conversion provides additional opportunities to
413 discuss substituent effects in aromatic systems. Many SP
414 derivatives have been synthesized, and they have different
415 photochromic properties as a result of the substituent
416 patterns.²⁰

417 ■ METHODS

418 Team Formation Process

419 Prior to the beginning of the semester, an effort was made to
420 create balanced cooperative-learning teams that each were
421 composed of learners with low, medium, and high relative prior
422 chemistry experience and demonstrated math skills. To this
423 end, students were placed into "semirandom" teams of four (or
424 five) individuals based primarily on rankings from relative self-
425 reported AP Chemistry exam scores. Math SAT scores are
426 known to highly correlate with performance in college-level
427 general chemistry courses,^{14,15,21} so Math SAT scores were

used as a secondary ranking. Teams were randomly assigned 428
team numbers (1–24) that were used to track team scores over 429
the entire course of the semester. More detail on the formation 430
of teams can be found in the [Supporting Information](#). 431

432 Experimental Design

To determine whether or not the SP applications work as well 433
in guiding students toward meeting desired unit learning 434
outcomes when compared to more traditional, small-molecule- 435
based applications we had previously used in Unit 4, a random 436
trial was devised. For Unit 4 only, the instructor drew a random 437
number that resulted in the odd-numbered teams being the 438
control group and the even-numbered teams being the 439
experimental group. To exclude bias, the researchers who 440
initially developed the application problems did not teach the 441
course during the semester that the formal assessment of its 442
implementation in the classroom was performed. 443

At the beginning of the unit on Molecular Orbital Theory, 444
both groups met at the same time and took the same IRAT and 445
TRAT (see [Supporting Information](#)). Next, to examine the 446
effectiveness of the new SP-based applications, the control and 447
experimental groups initially completed two unique sets of 448
applications in the subsequent class meetings. In unique class 449
periods, the control group teams completed the original 450
applications problems, while the experimental group teams 451
completed the redesigned SP-based applications (see [Support-](#) 452
[ing Information](#)). After completing each set of applications, 453
each team completed a Strategy Analyst report where, as a 454
team, they ranked both the difficulty of and their interest in the 455
application problems on a five point Likert-type scale. Teams 456
also had the opportunity to provide written feedback about the 457
strengths and areas for improvement for the set of applications 458
they completed on the Strategy Analyst report (see [Supporting](#) 459
[Information](#)). The Likert-type scale numeric values were 460
tabulated, and the written responses were transcribed by a 461
staff assistant not involved with the study. Averages, standard 462
deviations, and standard errors were calculated for each data 463
set, and an unpaired *t*-test was performed on the two group's 464
numerical responses to test for statistical significance. 465

After both groups met, separately, to complete the control 466
and experimental applications, the groups were remerged for 467
the next class period and all individuals in both groups 468
completed the same unannounced "pop" quiz. This quiz was a 469
LO-driven assessment composed of 10 multiple choice 470
problems. Each problem was coded to specific course learning 471
objectives with a focus on those covered in the Unit 4 472
applications (see [Supporting Information](#)). Following the 473
individual LO Assessment (pop quiz), each team completed 474
the set of applications they had not previously seen to ensure all 475
students were exposed to all the same application activities by 476
the end of the unit. Scores on the LO Assessment were 477
combined for each group and averages, standard deviations, and 478
standard errors were calculated. An unpaired *t*-test was 479
performed on the two sets of scores to test for statistical 480
significance. 481

482 ■ RESULTS

Before comparing the results of the application-based IRAT, 483
the results of the previous IRATs were compared for the 484
experimental and control groups. For the first three IRATs 485
taken as part of Units 1, 2, and 3, there was no significant 486
difference in scores between the control and experimental 487
groups ($0.39 < p < 0.70$) (see [Supporting Information](#)). A 488

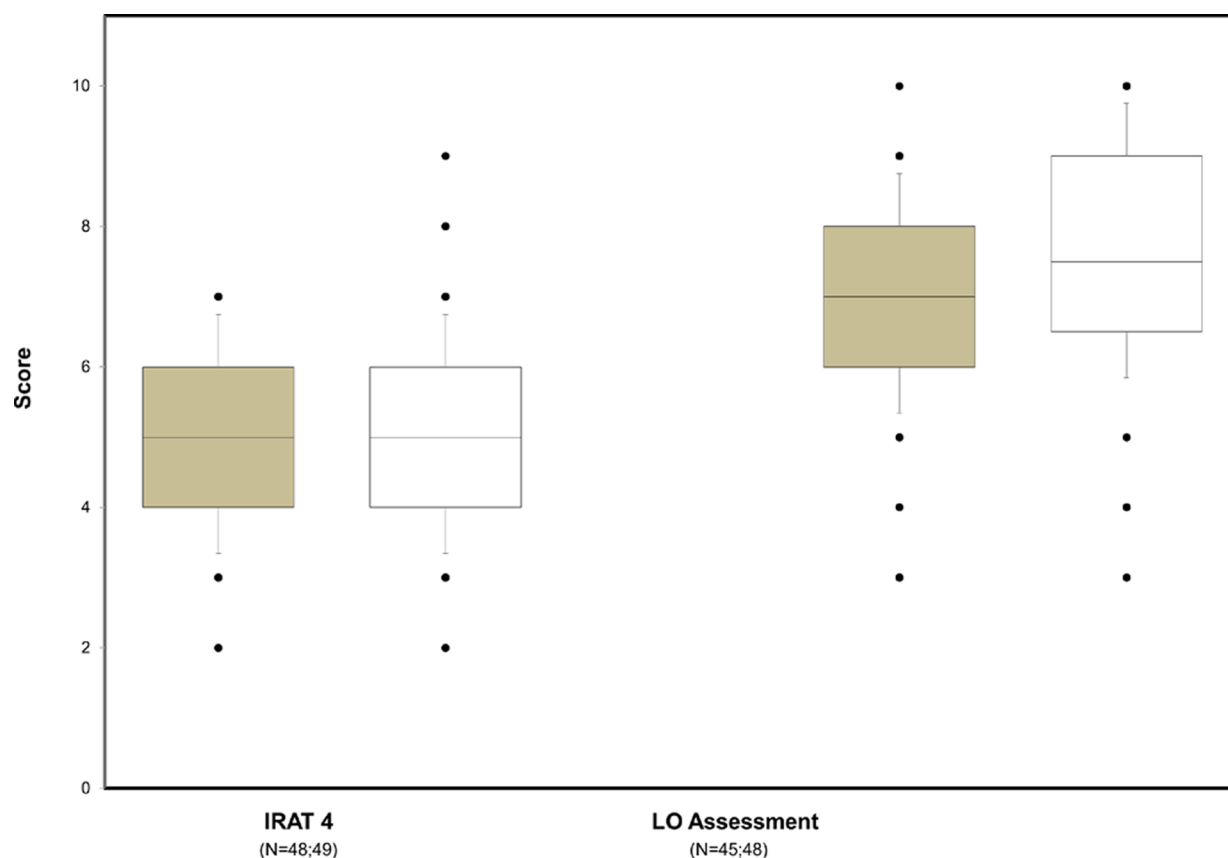


Figure 4. Initial Unit 4 IRAT and LO Assessment scores for control and experimental group.

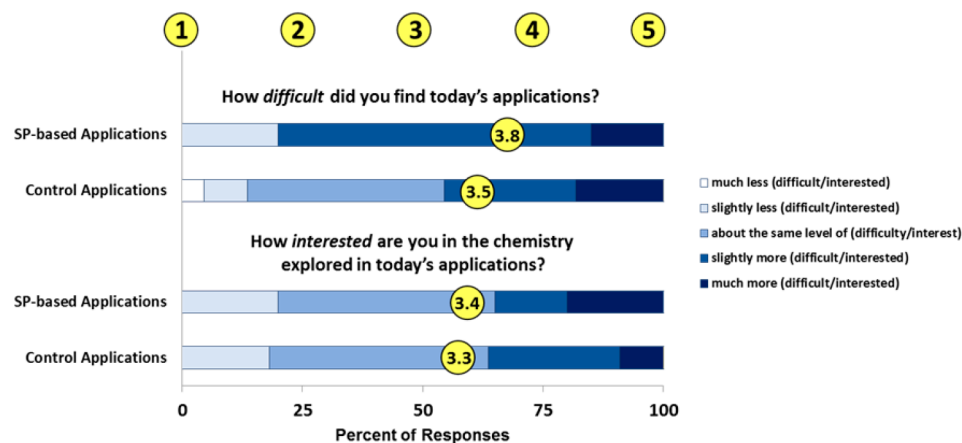


Figure 5. Student Likert-type scale feedback after completing each set of applications. Shading in bars corresponds to the percentage of responses (lower axis), and the average value on the Likert-type scale is indicated by the yellow circles on the graph (with position relative to reference values at top of figure).

489 comparison of results on the control and experimental group
 490 on both the initial IRAT for Unit 4 and LO Assessment (pop
 491 quiz) showed no statistical significance between the two groups,
 492 $p = 0.30$ and $p = 0.10$, respectively (Figure 4).

493 In addition to the assessment, students' responses to the
 494 Likert-type scale items and their written free-response feedback
 495 on the applications were analyzed. For the Likert-type scale
 496 questions, near the end of each class period, teams were asked
 497 to compare the day's applications to those completed for
 498 previous units and assess the relative difficulty of and their
 499 interest in the applications with 5 representing more difficult/
 500 more interested and 1 representing less difficult/less interested

(Figure 5). The unpaired t -test showed no statistical difference 501
 between the control and experimental groups, $p = 0.2757$ and p 502
 = 0.4154, respectively. Additionally, teams provided written 503
 feedback on the strengths of the applications as well as areas for 504
 improvement. Representative student feedback is shown in 505
 Table 2. Complete student feedback is available in the 506
 Supporting Information. 507

DISCUSSION

508
 A comparison of the initial Molecular Orbital Theory IRAT 509
 showed no statistical difference between the Control and 510
 Experimental groups. Therefore, prior to completing the 511

Table 2. Representative Initial Student Reactions to Control and SP-Based Applications

Prompt	Group	Representative Student Responses
Please list at least one strength of today's applications	Control	"It combined the topics we have learned in topic 2 and the one we are learning"
		"Makes to link molecular orbital to actual properties of the molecule"
		"We achieved a better understanding of MO Theory"
	Expt	"Ability to understand concepts of resonance and delocalization"
Please list at least one possible improvement to today's applications		"The exercises built on each other and connected to our lab"
		"The applications applied to the lab, which made it easier to understand"
	Control	"Questions more related to each other"
		"They could have been more in depth"
	Expt	"Understanding applying force energetically"
	"The questions should be more clear. For example, the last application should have indicated that the Spartan model was needed."	

512 application problems, both groups start from a similar initial
513 baseline. After completing the different sets of application
514 problems, both groups showed a similar level of mastery of the
515 course learning objectives, based on the LO Assessment, with
516 no statistical difference between the Experimental and Control
517 groups. Students also provided similar feedback on the difficulty
518 level and their interest in the chemistry content of both sets of
519 applications problems, with generally neutral feelings toward
520 the difficulty and their interest in the chemistry.

521 Even though there is little difference in the quantitative
522 measures, students expressed unique written feedback on the
523 application problems, with some students in the Control group
524 noticing the disconnection between the application problems
525 while some students in the Experimental group noticed
526 connection within the application set and in the laboratory
527 experiment they had recently performed.

528 ■ LIMITATIONS

529 Limitations in this study were present in both the size of the
530 sample as well as the method used to assess student learning
531 outcomes. Due to the class size, the control and experimental
532 groups were limited to approximately 50 students each, which
533 limits our ability to observe statistical differences given the
534 small sample size. Maintaining consistency within the course
535 format, only one strategy analyst sheet is collected per team,
536 which shows only the team's net assessment on the difficulty
537 and interest in the SP-based applications. This team-based
538 feedback does not take into account individual students'
539 assessments of the application problems, which may have
540 differed somewhat from that of the whole team. Additionally,
541 the LO Assessment was administered as a multiple choice quiz,
542 similar to the IRATs the students had been previously exposed
543 to, which could allow students to make an informed guess of
544 the correct answer without a deeper understanding of
545 underlying concepts.

546 ■ SUMMARY AND PERSPECTIVES

547 The SP/MC module described here directly addresses several
548 learning objectives commonly covered in general chemistry
549 courses, but in the context of polymers and introductory
550 organic chemistry principles. The use of one reaction as a
551 common thread by which to tie together concepts typically
552 presented as disparate entities allows the students to explore
553 the factors that contribute to the organic transformation
554 between SP and MC, highlighting molecular orbital theory,
555 quantum mechanics, equilibrium, hydrogen bonding, and work
556 while also introducing basic concepts of polymer chemistry. We

have found this exercise to be a useful way to structure a 557
portion of a general chemistry course in order to address the 558
interdisciplinary nature of chemistry and enhance students' 559
understanding of real-world applications of general chemistry 560
topics. The Craig group's initial interest in the SP-to-MC 561
conversion inspired this work, and students seem to enjoy 562
learning about research at their university. We hope our 563
experience encourages other researchers and educators to adapt 564
their scientific interests to the courses that they teach. 565

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS 568
Publications website at DOI: 10.1021/acs.jchemed.7b00977. 569

Complete list of the course learning objectives, copy of 570
the laboratory experiment, information on the in-class 571
demonstrations, control and SP-based application 572
problems, Unit 4 IRAT and LO Assessment, and student 573
feedback (PDF) 574

■ AUTHOR INFORMATION

Corresponding Authors

*E-mail: dorian.canelas@duke.edu. 577

*E-mail: stephen.craig@duke.edu. 578

ORCID

Meredith H. Barbee: 0000-0002-7324-2866 580

Cameron L. Brown: 0000-0002-9616-2084 581

Stephen L. Craig: 0000-0002-8810-0369 582

Author Contributions

†M.H.B. and R.G.C. contributed equally. 584

Notes

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