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Bringing in the Bard: Shakespearean Plays as Context for Instrumental Analysis Projects

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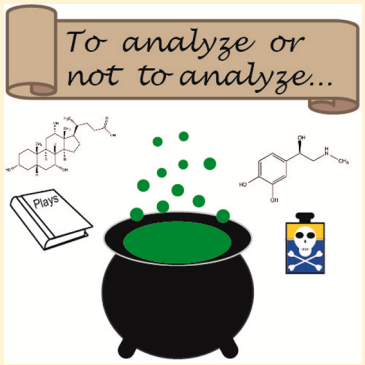
Supporting Information

ABSTRACT: Scenes from the works of William Shakespeare were incorporated into individual and group projects for an upper-level chemistry class, instrumental analysis. Students read excerpts from different plays and then viewed a corresponding video clip from a stage or movie production. Guided-research assignments were developed based on these scenes. These projects required students to make significant use of primary scientific literature to address open-ended research questions inspired by Shakespearean plays. Projects were scaffolded with in-class activities to guide and encourage student progress. Class performance, student perceptions, and learning outcomes will be discussed, and a student perspective is included. Recommendations for the incorporation of Shakespeare into other chemistry courses are provided.



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A series of projects was developed that uses liberal arts content to suggest analytical problems for the upper-level course, instrumental analysis. Previously, students were provided with research questions taken directly from events reported by the media. Context-based examples can highlight appropriate design of research questions and methods, a task that is often challenging to students;[1−3] however, these media-inspired chemical issues had the unanticipated problem of having answers too available in the literature since chemists were already publishing solutions. Students would then merely provide an article summary and disregard any instrumentation or sampling information presented in class. Students needed context without a neatly packaged solution available in the literature to address the misconception that there is only one "correct" answer to every chemical problem. New sources of chemical problems were needed to improve instrumental analysis assignments.

The introduction of chemical concepts in an interdisciplinary context is a creative approach that promotes critical thinking.[4−7] Chemistry classes have been supplemented with material from such liberal arts subjects as music,[8−10] history,[11−13] literature,[14−19] performing arts (extended here to include film),[20−27] and visual arts.[28−31] These examples prompted a redesign of assignments for instrumental analysis. Plays by William Shakespeare were used to provide students with interdisciplinary inspiration for class assignments. The desired learning outcomes included (1) reinforcement of course material, (2) practice with research design, and (3) creative integration of chemical literature with course material.

In addition to utilizing liberal arts material, the projects described herein included a scaffold of in-class activities to guide students toward a more creative and independent design of research questions and methods. Scaffolding, which here refers to guidance provided by the instructor to students, aids students in complex problem solving by making material more accessible, building student confidence, and modeling appropriate integration of prior knowledge with new skills.[32−35] Others have implemented scaffolded learning via a variety of modes including laboratory work,[36,37] web-based programs,[38,39] and class activities.[40−42] In the Shakespeare-inspired projects described here, the amount of direct guidance provided in the activities decreased over the course of the semester, while the project tasks increased in demand on student independence and responsibility.

INSTITUTION AND COURSE BACKGROUND

Mercer University is a comprehensive, medium-sized institution with the Department of Chemistry housed in the College of Liberal Arts (CLA). Students in the CLA are required to complete one of two general education programs of liberal arts coursework in addition to their declared major(s) and minor(s). Although the exact courses in each program differ, both general education paths require three writing-instruction courses.

Instrumental analysis (CHM 341) is a lecture course with prerequisites of organic chemistry II and quantitative analysis. Over the duration of 16 weeks (15 full weeks of instruction), instruction is split approximately into three parts: separations, mass spectrometry, and spectroscopy. Students learn the theory

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and instrumentation required for each technique, including gas and liquid chromatography, electrospray ionization mass spectrometry, infrared absorption spectroscopy, fluorescence spectroscopy, and electrochemical and surface techniques.

■ ACTIVITY DESIGN

Play Selection and Incorporation

At week four of the semester, students were given an anonymous survey to determine (1) previous exposure to Shakespeare's works and (2) student perception of liberal arts in the chemistry classroom prior to the new assignments. Students were asked to indicate which Shakespearean comedies, tragedies, and histories they had read previously (Supporting Information, Table S1). A separate list asked students to indicate which plays they had some familiarity with or had seen a film or stage adaptation of, even if they had not read the full play. The number of Shakespearean plays read prior to the course ranged from one to six, with a class average of four works read; however, there was not a play common to all students. *Hamlet* and *Macbeth* were selected for use in the course because of the (1) students' self-reported familiarity with the plays, (2) prevalence of analyte-rich scenes, and (3) use of their themes and plots in popular culture.

Scenes used in the projects were read and viewed by students during class time (Table 1). Students were given the corresponding lines at the start of class, and they read the script once before they viewed a video clip from a movie or stage production. Following this the instructor led the class through a summary of the scene and provided its relation to the overall plot if necessary. The in-class viewing and informal discussions of the Shakespearean scenes provided students with common experiences. This common experience is especially important when students have different prior exposure to liberal arts coursework.

Project 1: Sampling Shakespeare's Ghost

The primary learning objective for the assignment was for students to develop an appropriate analytical method for a specified analyte in a complex matrix. The analyte/matrix combinations were inspired by a scene in Act 1, scene 5 of *Hamlet*.[43] In the scene, the title character is visited by the ghost of his father. The ghost explains to Hamlet that he was murdered by poison given by his uncle. The ghost asks Hamlet to avenge his death, particularly because the uncle not only is now the king of Denmark, but also married Hamlet's mother. Students read the scene and then watched the corresponding excerpt from a film adaptation, which included a reenactment of the poisoning.[44] Immediately after viewing the film clip, students were asked to write down as many combinations of analytes and matrices that they observed in the ghost scene. Some examples of the matrices the students found particularly compelling included the ghost, vapors coming out of the ground, the surrounding environment, and the poison mixture. After the students brainstormed independently for a few minutes, they compared ideas in small groups and ultimately generated a master list as a class. The instructor used this list to generate research questions based directly from the text (Table 2).

This project was assigned in week seven of the semester, so students already had exposure to several types of mass spectrometry and a variety of separation techniques, including gas chromatography, high performance liquid chromatography, and capillary electrophoresis. Students were asked to research

Table 1. Schedule of Scaffolded Shakespeare Assignments

Shakespeare assignment[a]	class activity	semester week	class meeting	required class time
#1–*Hamlet*	read, watched, and discussed the scene with Hamlet interacting with the ghost (1.5.3–67)	7	17	10 min
analyte and corresponding research question provided	proposal of analytes inspired by scene	7	17	10–15 min
	discussion of assignment and rubric	7	18	5–10 min
	student verbal update on project progress	8	19, 21	5–10 min
	project due; class discussion of results	9	22, 23	2 class meetings
#2–*Macbeth*	read, watched, and discussed witches' brew scene (4.1)	12	32	10 min
analyte provided; students design appropriate research question	discussion of assignment and rubric	12	32	5–10 min
	student written update on project progress	13	35	5 min
	peer workshop to discuss project ideas	13	35	45 min
	project due; small group discussion of results	14	36	15 min
#3–student choice	discussion of assignment and rubric; class selection of groups	14	38	10 min
analyte selected and research question developed by students	updates on group progress	15, 16	39, 40	15 min
	project due; group presentations	16	41, 42	2 class meetings

[a]Assignment descriptions, rubrics, and workshop handouts are included in the Supporting Information.

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Table 2. Selected Project #1 Topics Provided by the Instructor with Input from Students

topic[a]	line	citation
analysis of sulfur content in gases from purgatory vapors	"My hour is almost come/When I to sulph'rous and tormenting flames/Must render up myself."	*Hamlet* 1.5.3−4
analysis of hebenon concentration in the vial mixture (an oil)	"Upon my secure hour thy uncle stole/With juice of cursed hebenon in a vial."	*Hamlet* 1.5.61−62
analysis of the rash and/or excretions for poison	"...with vile and loathsome crust/All my smooth body..."	*Hamlet* 1.5.72−73
analysis of Denmark snow for pollution	"...tis bitter cold."	*Hamlet* 1.1.8
analysis of brain tissue for poison	"...that swift as quicksilver it courses through/The natural gates and alleys of the body..."	*Hamlet* 1.5.66−67
analysis of adrenaline in the body (matrix student choice)	"Make thy two eyes like stars start from their sphere/Thy knotted and combined locks to part/ And each particular hair to stand on end..."	*Hamlet* 1.5.17−19

[a]Analyte−matrix combinations were inspired by specific lines from *Hamlet*.

Table 3. Selected Project #2 Topics Developed by Students

Macbeth ingredient[a]	student-developed research question
baboon blood	determination of mercury in baboon blood using inductively coupled plasma mass spectrometry
bat fur	detection of organochlorine pesticides in bat fur with mass spectrometry
gall of goat	separation and quantification of cholic acid in goat bile with high performance liquid chromatography and electrospray ionization mass spectrometry
hemlock root	identification of coniine in hemlock using chemical ionization mass spectrometry
toad	quantification and identification of bufotoxins in the common toad with UV−vis spectroscopy and mass spectrometry
wolf tooth	amount of hemoglobin isolated from a wolf tooth determined by UV−vis spectroscopy and electrospray ionization mass spectrometry

[a]Ingredients are given in *Macbeth* 4.1.

the analyte and matrix in their assigned topic using the chemical literature and combine what they found with previously learned class material to develop an appropriate sampling scheme. Final projects were required to include the proposed analysis scheme and a corresponding written section. This section included definitions of new terms, a rationale for the proposed analysis, and a summary of expected data. Students worked on their projects outside of class time and supplemented what they learned in class with new information from the scientific literature. Additional scaffolding occurred at week eight, when students were asked to give an informal update on their project progress to the whole class. The instructor gave brief feedback in class on each update. These informal updates occurred twice before the project due date. Students also were encouraged to make out-of-class appointments with the instructor to continue to discuss progress.

The project was due on week nine of the semester. Students gave informal presentations during an in-class, round-table discussion. Members of the class were provided copies of each student project, which enabled a thorough discussion of each step of the proposed analysis scheme. The informal discussion enabled students to learn about a wide range of analytes and matrices in addition to their assigned topic, and thus this assignment not only guided students in their research design, but also helped develop their scientific communication skills.

Project 2: "Double double toil and trouble..."

The second Shakespearean project was assigned at week 12 of the semester and due on week 14 (Table 1). Students read and watched Act 4, scene 1 of *Macbeth*, which includes a detailed recitation by the witches of their potion's recipe.[45] During the discussion of the scene, unfamiliar components were defined for the students. While the *Hamlet* assignment provided students with a project topic, this assignment required students to develop their own research question for investigation based on the analytes described by Shakespeare's witches. To successfully complete the project, students needed to learn about their selected *Macbeth* analyte in order to make an informed decision about a scientifically interesting research question. For example, the student who chose the "owlet's wing" (*Macbeth* 4.1.17) learned that birds often have coatings on their wings; the student used this information to design a research question on the amount of fatty esters present on owl feathers (Supporting Information). Other student research questions are provided in Table 3.

Student progress on this more challenging project was encouraged and guided with several in-class exercises. At week 13, students were asked to spend several minutes summarizing their project progress based on a written prompt (Supporting Information). The instructor used these responses to put the students into groups of three or four students based on their self-reported progress. For example, students who had completed a draft of their analysis schematic were paired up, while those who had not yet defined a research question were grouped together. The peer workshop was based on a worksheet that guided students through a discussion about their project ideas (Supporting Information). After completion of the worksheets, the instructor led a class discussion to summarize the peer workshops. During the discussion, students shared their suggestions, and the instructor provided feedback on the research questions and proposed methods.

At the class meeting after the assignment due date (week 14), students were put into random groups of three or four to discuss their work. After about 10 min of discussion, students were asked to summarize their favorite projects to the class. In this way, students learned not only while they researched and assembled their projects, but also from their peers during small group discussion. This class discussion also gave students an additional opportunity to critically assess research questions and methods proposed by their peers, which parallels the analysis they had already performed of the chemical literature.

Project 3: Bringing Back the Bard

The final project, which involved a teaching presentation about an instrumental technique, was completed by groups of three to four students. Students were asked to suggest final presentation

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Table 4. Project #3 Research Questions Developed by Students for Assigned Instruments

instrumental technique	analyte	research question	Shakespearean inspiration
atomic force microscopy	red blood cells	Did the poison on the pearl affect the Queen's blood by either decreasing her red blood cell count or causing her red blood cells to shrivel?	*Hamlet* 5.2.308−310
scanning tunneling microscopy	silver nanoparticles	What are the shapes and dimensions of synthesized silver nanoparticles?	*Macbeth* and *Hamlet* (metal cups)
isothermal titration calorimetry	cytochrome c oxidase	What is the binding affinity for cyanide to cytochrome c oxidase?	*Romeo and Juliet* 5.3.118−120
X-ray fluorescence	metal	What metals are found in fertile soil?	*Romeo and Juliet* 2.3.9−10

Table 5. Course Survey Results for Instrumental Analysis (CHM 341)[a]

statements for response	mean (SD)	agree or strongly agree (4/5), (%)	disagree or strongly disagree (1/2), (%)
Pre-Activity Questions			
1. I value my liberal arts coursework.	3.2 (1.4)	50	36
2. My previous chemistry courses incorporated liberal arts material.	1.9 (0.9)	7	79
3. Making connections to other disciplines helps reinforce course material in CHM 341.	3.5 (1.1)	50	14
4. I would like CHM 341 to include more liberal arts connections.	2.7 (1.1)	21	43
5. The idea of incorporating Shakespearean examples into CHM 341 appeals to me.	2.9 (1.2)	36	14
6. I am comfortable with reading excerpts of Shakespeare's work.	3.6 (0.7)	57	7
7. The idea of incorporating Shakespearean examples into CHM 341 makes me anxious.	2.8 (0.8)	7	29
Postsemester questions			
1. I value my liberal arts coursework more as a result of completing CHM 341 Shakespeare assignments.	2.9 (1.2)	31	31
2. Making connections to other disciplines helps reinforce course material in CHM 341.	3.9 (0.6)	77	0
3. I believe that CHM 341 should continue to include liberal arts connections.	3.4 (1.0)	38	8
4. I believe that CHM 341 should continue to utilize Shakespeare in assignments.	3.0 (1.3)	38	23
5. I am more comfortable reading excerpts of Shakespeare's work after completing CHM 341.	3.2 (1.1)	38	23
6. After completing this course, I am less anxious about the idea of incorporating Shakespearean examples into CHM 341.	3.6 (1.0)	62	15
7. The Shakespeare assignments helped me to learn CHM 341 related material.	3.6 (1.1)	69	15
8. The Shakespeare assignments helped reinforce CHM 341 related assignments.	3.6 (1.0)	77	15
9. The Shakespeare assignments helped me to improve my understanding of sample preparation requirements.	3.9 (1.1)	77	8
10. The Shakespeare assignments helped me to improve my understanding of the chemical literature.	3.5 (1.1)	62	15
11. The Shakespeare assignments helped me to improve my critical thinking skills.	4.0 (0.6)	85	0
12. I am more comfortable creatively approaching scientific problems as a result of the Shakespeare assignments.	3.5 (0.9)	54	15

[a]Likert scale: 5, strongly agree; 4, agree; 3, neutral; 2, disagree; 1, strongly disagree. Surveys were anonymous. Preactivity surveys were completed by 14 of the 14 enrolled students. Postsemester surveys were completed by 13 of the 14 enrolled students.

instrument topics. In fall of 2013, the four instrumental techniques chosen by the class were atomic force microscopy, scanning tunneling microscopy, isothermal titration calorimetry (ITC), and X-ray fluorescence. The corresponding presentations needed to cover the purpose and main components of the assigned instrument. For a Bard-related twist, sample data for the instrument had to be discussed for an analyte inspired by Shakespeare or his works. This extended the previous two assignments because students were required to (1) pick an appropriate analyte, (2) connect it to Shakespeare, and (3) discuss an investigation appropriate for the assigned instrument. Thus, this third project required students to come up with both the analyte and appropriate research question. For example, the group that presented ITC used the final poison scene in *Romeo and Juliet* as inspiration to discuss how ITC could be used to investigate the interaction of another poison, cyanide, with cytochrome c oxidase.[46,47] The four instruments and student-generated research questions are listed in Table 4. The project description and rubric were discussed in week 14, and groups were asked for a verbal update in class in weeks 15 and 16. After each group shared a brief summary of their group progress, the instructor guided an informal class discussion to generate group feedback. The last two lectures of the semester were devoted to the group teaching presentations.

Scaffolding Activities

Before the introduction of the scaffolded Shakespeare-inspired projects, students in instrumental analysis struggled with the open-ended nature of chemical research problems. Rather than integrate information from the chemical literature with course information, students over-relied on finding solutions in single publications. Use of liberal arts material as prompts for research design decreased the probability that one journal article contained an appropriate solution, but students also needed more structured guidance for the research design process. According to Bean, undergraduate students, regardless of discipline, are not accustomed to generating their own thesis statement or research question, so this is not a problem unique to analytical chemistry.[48] Scaffolding, the process of selecting and refining a research question, gives students the tools and

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feedback needed to achieve independence in successful research proposals.[33,34]

The three projects provided a scaffold for research design in the context of Shakespearean works by gradually decreasing the amount of guidance provided to the students (Table 1). Specifically, students worked together in class to suggest analytes that the instructor then refined into a final list of research questions for the first project. The second project provided a list of analytes to the students via a scene from *Macbeth*, but students were responsible for designing a research question pertaining to a property of the analyte. The final project required groups of students to work together to identify both an appropriate analyte and corresponding research question. In-class, instructor-facilitated activities also guided student progress toward independence in critical analysis of the chemical literature. The total time required for all in-class activities, excluding project presentations, was approximately 140 min (Table 1).

STUDENT FEEDBACK

Student Perceptions

Anonymous surveys were given before and after implementation of the Shakespeare instrumental analysis projects. Students were given a series of statements and asked to respond to them with a five-point Likert scale (Table 5). Preactivity questions indicated that students had mixed feelings presemester about liberal arts material and its incorporation into instrumental analysis. Half of the class at the start of the semester agreed or strongly agreed that they valued their liberal arts coursework, but more than a third of the class disagreed with the statement. Student response indicated a lack of experience with liberal arts material in prior chemistry coursework, so it is not surprising that 43% of the class indicated at the start of the semester that they did not want more liberal arts connections in the course. One student even indicated in the free response section of the survey that "this is a science class NOT an English class." This reaction only underscores the need for these assignments; even students enrolled in a liberal arts college may struggle to see relationships between disciplines, particularly to those outside of the sciences. Interdisciplinary work promotes deeper and more critical thinking, and students benefit from thoughtful assignments that model for them where and how interdisciplinary connections exist.

Student perception of the benefits of these projects was overall positive. The majority of the class agreed that the Shakespeare assignments helped them to learn and reinforce class material. Most of the students also agreed that the assignments helped improve their understanding of the literature and sample preparation requirements. Approximately half of the class agreed that they are more comfortable with creatively approaching scientific problems as a result of the Shakespeare projects. Most significantly, 85% of the class agreed or strongly agreed that the Shakespeare assignments improved critical thinking skills. These student perceptions are supported by the observations of the instructor. By the end of the semester, students were more confident in research design and more skilled in the use of chemical literature than students were in previous years. An additional student perspective is included in the following section.

A Student Perspective

"To me, the most interesting parts of the project were the analytes. The analytes each class member was given to examine were exotic and strange, such as bat wings and owl feathers. The unique nature of these analytes made designing a sample preparation scheme very challenging. When my classmates and I were tasked with devising sample preparation schemes for these analytes, we were forced to do heavy research and suggest creative methods. I found that I had to combine sample preparation methods from multiple journal articles in order to devise a suitable preparation scheme.

I also found the public speaking aspect of the assignments to be very useful. Presenting my proposed preparation and analysis schema required me to thoroughly understand my topic because I knew that any gaps in my knowledge would be evident to both the instructor and the class. In addition, I got to hear about other interesting analytes and examination techniques from my classmates.

The Shakespeare projects certainly deepened my understanding of instrumental analysis. Being forced to solve unique problems helped me realize a part of what it must be like to test a new or unknown substance in the lab, and they taught me about a variety of advanced instrumentation. These problems helped me understand how advanced instrumental methods can be applied to real life issues. I recommend using similar assignments in any instrumental analysis class."

SUMMARY AND RECOMMENDATIONS

Shakespearean plays were incorporated into instrumental analysis class projects. Although some students were uncomfortable with the liberal arts material included in the assignments, student learning, class engagement, and final project products improved. Requiring students to utilize information from diverse disciplines resulted in higher-order learning and reinforcement of scientific communication skills. These interdisciplinary connections benefit all students, not just those at liberal arts institutions. Scaffolding individual assignments to involve in-class components encouraged consistent and engaged work. The combination of projects with scaffolded, in-class activities provided a developmental progression for student design of research questions and methods. The instructor and a majority of the class found these creative assignments to be engaging, interesting, and fun.

The activities described here could be adapted to other chemistry courses. For example, students in biochemistry could investigate the biochemical pathways impacted by various poisons, while inorganic chemistry students might investigate the properties of metals used in weapons, all by taking inspiration from *Hamlet*. Showing excerpts of film adaptations provides a common, engaging class experience; however, if class time is a concern, students could be required to view video clips prior to lecture. Similarly, the in-class group discussions could be adapted to online discussion groups in course management systems or wikis, with the results tabulated by the instructor. Future iterations of these assignments in instrumental analysis will focus on different plays of Shakespeare or other literary works.

ASSOCIATED CONTENT

Supporting Information

A list of Shakespeare's plays, student self-reported familiarity with the plays, assignment descriptions, grading rubrics, examples of in-class activities, and samples of student work. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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