JOURNAL OF CHEMICAL EDUCATION
Article
pubs.acs.org/jchemeduc

Rethinking Undergraduate Physical Chemistry Curricula

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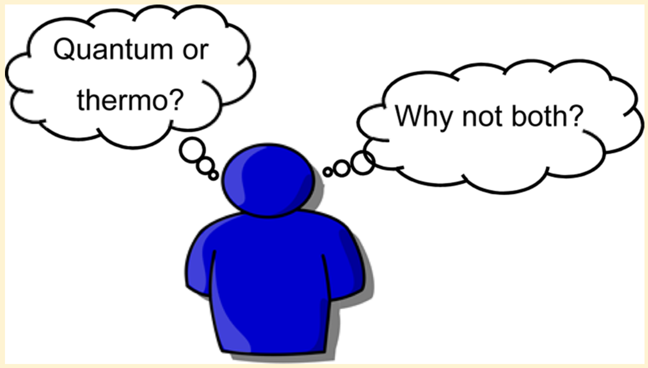
Supporting Information

ABSTRACT: A summary of fundamental changes made to the undergraduate physical chemistry curriculum in the Chemistry Department at Gustavus Adolphus College (beginning in the 2013–2014 academic year) is presented. The yearlong sequence now consists of an introductory semester covering both quantum mechanics and thermodynamics/kinetics, followed by a second semester that covers more advanced and integrated topics. While the initial rationale for changing the physical chemistry sequence was to improve the department's overall curriculum, the process has raised some important questions about the propriety of the traditional approach to physical chemistry education in the 21st century.



KEYWORDS: *Upper-Division Undergraduate, Curriculum, Physical Chemistry, History/Philosophy, Testing/Assessment, Professional Development, Quantum Chemistry, Thermodynamics*

INTRODUCTION

Recent Trends in Chemical Pedagogy

Like practitioners in any field, chemists must constantly think about the curricula they offer their students and how current/coming trends will (or should) impact those curricula; this is true for disciplinary and subdisciplinary curricula alike. Some examples of this type of forward thinking include a series of ACS symposia (and the subsequent report[1]) focused on chemistry education in the 21st century, reimagined department-level curricula,[2] modifications to early career coursework,[3] and the rethinking of subdisciplinary content.[4,5] At the same time, instructors have begun to consider how to diversify pedagogical approaches in the classroom; for example, the idea of "flipped classrooms" was the topic of the Spring 2014 ConfChem,[6] and traditional lecture has been increasingly replaced by alternatives such as process-oriented guided inquiry (POGIL)[7] in the classroom.

However, the basic structure of undergraduate physical chemistry curricula has remained relatively unchanged, even as other chemical subdisciplinary curricula have started to become more varied and classroom pedagogies have diversified. Fox and Roehrig recently published the results of a survey regarding undergraduate physical chemistry education.[8] While their survey included questions about many facets of physical chemistry education, one of their key findings (as far as this report is concerned) was as follows:[8]

"[A]lmost all (>99%) institutions represented in the survey divide physical chemistry into one semester of thermodynamics and one semester of quantum mechanics."

Furthermore, Fox and Roehrig state that there are "similarities in beliefs of instructors regarding how similar physical chemistry courses are and should be";[8] in other words, most instructors agree that it is appropriate for physical chemistry to be divided and taught in this fashion.

Chemistry at Gustavus Adolphus College

Gustavus Adolphus College (GAC) is a four-year residential liberal arts college located in St. Peter, Minnesota. The Chemistry Department offers three primary undergraduate degrees: an ACS-approved chemistry major (ACS), typically pursued by students interested in graduate school in chemistry or a related field; a reduced-content liberal arts perspective (LAP) chemistry major, often pursued by students interested in postgraduate health profession programs; and a biochemistry/molecular biology (BMB) major, offered as an interdisciplinary program with the biology department. Over the past five years, the GAC Chemistry Department has awarded 178 degrees to 160 students (Table 1), or a five-year average of ∼35 degrees awarded to 32 students per year.

Part of the departmental curriculum is a two-semester sequence in physical chemistry (CHE 371 and CHE 372) that is typically taken by students in their third or fourth year. Of the three degree programs, only the ACS track requires students to complete both semesters of physical chemistry; the BMB and LAP majors, which represent 93% of graduates (and 94% of earned degrees) over the previous five years, only require the completion of CHE 371.

Prior to the 2013–2014 academic year, the CHE 371/372 sequence had a very traditional structure: thermodynamics and

Received: November 23, 2015
Revised: May 24, 2016

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 1. Graduation Data and Physical Chemistry Enrollments at GAC Since 2010−2011

Academic Year	2010−2011	2011−2012	2012−2013	2013−2014	2014−2015	Total
ACS degrees	4	1	2	2	2	11
LAP degrees	22	18	18	26	19	103
BMB degrees	12	10	14	11	17	64
Total degrees awarded	38	29	34	39	38	178
Number of graduates	30	28	30	37	35	160
CHE 371 enrollment[a]	27	27	42	28	33	157
CHE 372 enrollment	4	2	5	4	5	20

[a]The total CHE 371 enrollment and the total number of graduates are slightly different due to the mix of third- and fourth-year students in CHE 371.

Table 2. Representative Breakdown of Topics Covered in CHE 371/372 Prior to and Following Curricular Changes

	2010−2011		2014−2015		
Topic (Relevant Textbook Chapters)[a]	Course	# Days	Course	# Days	Significant Changes in the Course Curriculum
Math background	371/372	5	371	3	Sporadic topics from throughout the curriculum collected and presented in a dedicated unit; time reduced by presenting information in summary fashion
Roots of QM (1)	372	3	371	3	None
Postulates of QM (4)	372	3	371	3	None
Model QM systems (3, 5)	372	4	371	5	Removed statistics background to the math background unit; additional discussion of conceptual aspects, such as tunneling
Atomic structure (6, 8)	372	7	371	5	Reduced coverage of term symbol determination to only ground states
Chemical bonding (9, 10)	372	6	371	4	No change in coverage of diatomics; polyatomic MO theory briefly introduced in a very qualitative fashion
Basic spectroscopy (5, 13)	372	3	371	2	Only basic spectra (no coupling) and selection rules covered
Equations of state (16)	371	2	371	2	None
Classical thermodynamics (19−22)	371	10	371	8	All statistical mechanics removed
Activity (24, 25)	371	2	371	2	None
Equilibria (26)	371	4	371	3	None (content was compressed due to academic calendar considerations)
Basic kinetics (28, 29)	371	3	371	2	Limited to rate laws, method of initial rates, and useful examples (e.g., Michaelis−Menten kinetics)
Approximation methods (7)	372	4	372	4	Combined with polyatomic MO theory to demonstrate quantitative electronic structure modeling
Group theory (12)	372	5	372	4	Reduced coverage of purely mathematical background for group theory
Computational chemistry (7, 11)	372	2	372	4	Content greatly expanded to include introductions to basis set construction, multireference theories, electron correlation, and density functional theory
Advanced spectroscopies (13)	372	4	372	5	Impact of spectral coupling (e.g., vibronic spectra) and expanded coverage of ionization methods
Partition functions (17, 18)	371	6	372	4	Coverage of the concept of quantization removed; no other changes
Statistical mechanics (19−22)	371	2	372	5	Completely removed from classical thermo; presented in a distinct and more complete fashion
Phase equilibria (23−25)	371	5	372	5	None
Kinetic-molecular theory (27)	371	3	372	2	None (time reduction primarily the result of better student understanding of underlying math)
Transition state theory (28)	371	1	372	3	Expanded to include transition state thermo and stat mech descriptions of reaction mechanisms
Chemical mechanisms (28, 29)	371	2	372	4	Expanded coverage of the relationship between reaction dynamics and kinetics
The solid state	N/A	0	372	2	New unit on solid state concepts (such as band gap theory and magnetism)
Lasers and time-resolved spectroscopy	N/A	0	372	2	New unit on basics of laser operation, types, uses; reaction dynamics on short time scales
Total number of days	371/372	86	371/372	87	Allows time for review, exams, and the necessary adjustments to the schedule that typically arise

[a]Listed chapters roughly indicate the textbook[11] source material for each topic.

kinetics was covered in CHE 371 (Thermodynamics and Kinetics), and quantum mechanics was covered in CHE 372 (Quantum Chemistry and Dynamics). Because of the degree requirements, the vast majority (~90%, according to the data in Table 1) of our students were, prior to 2013−2014, graduating with a full semester of thermodynamics, but with virtually no exposure to quantum mechanics. We were leaving a significant gap in the educations of most of our students by providing them virtually no exposure to the most fundamental principles of modern chemistry.

The Need for a Change in Physical Chemistry

Considering the shortcomings of the extant curriculum, the Chemistry Department decided to find a way to better serve its LAP/BMB students. Initially, our goal was to develop a one-semester course that would introduce students to both quantum theory and thermodynamics and would be an alternative to the full CHE 371/372 sequence. This new course was envisioned as being much more in line with the recommendations of the ACS Committee on Professional

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

Training (CPT),[9] which clearly state that a one-semester physical chemistry course is only effective if it contains elements of both quantum mechanics and thermodynamics, and some of the content gaps are addressed in other courses. While not specifically intended to meet the CPT's guidelines (as it would not have targeted students in the ACS degree track), this hypothetical course would have better served BMB and LAP majors alike by being much more philosophically aligned with the CPT's model for an effective one-semester physical chemistry course.

However, there were two major difficulties for implementation of this model at GAC. First, staffing limitations required that any changes would have to be made in a faculty full-time equivalent-neutral way, limiting us to the teaching load (two lecture and four laboratory sections) normally associated with physical chemistry. This was incompatible with developing a new one-semester course while continuing to offer the original two-semester sequence (which was still needed by ACS majors). Second, we wished to offer the curriculum in such a way that students would be able to take CHE 372 (which is a senior-level elective course for LAP/BMB majors) after completing the proposed one-semester course without any significant gaps (or redundancies) in their learning. This was again at odds with the very nature of the pre-2013 CHE 371/372 sequence, in which CHE 372 was devoted entirely to quantum mechanics.

■ CHANGING THE PHYSICAL CHEMISTRY CURRICULUM

Changes Made to the Curriculum

It became evident that the proposed one-semester course was not a practical means of improving our physical chemistry curriculum. Other potential solutions either represented no real improvement (e.g., requiring LAP/BMB students to complete CHE 372 rather than CHE 371, which would have addressed the quantum gap by introducing a thermodynamics gap instead) or were nonstarters (e.g., requiring all students to complete both courses). The only way to simultaneously address all of the concerns was to teach elements of both thermodynamics and quantum mechanics in CHE 371. It was therefore decided to reinvent the entire CHE 371/372 sequence: CHE 371 (renamed "Physical Chemistry I") would cover fundamental topics in both quantum mechanics and thermodynamics, while CHE 372 (Physical Chemistry II) would cover more advanced topics—especially those that combine elements of quantum theory with thermodynamics. This is not a truly unique paradigm,[10] but it is exceedingly rare (as stated above, Fox and Roehrig report that <1% of physical chemistry curricula in the United States follow this model).[8]

The new version of the physical chemistry sequence was first offered during the 2013−2014 academic year. A representative breakdown of the topics covered in each class—including the number of class days spent on each and significant changes to each—both before (2010−2011) and after (2014−2015) the change—is included in Table 2. Much of the content ultimately remained the same, but some notable changes were effected.

Major Impacts of the Change

The most immediate positive change is that certain topics are given much more effective treatment in the new curriculum because of their timing; for example, statistical mechanics now receives more effective coverage as it occurs after students have been introduced to the principles of quantization. Student understanding of those topics has consequently improved, as has student receptivity to them. Using the same example, statistical mechanics, which was originally taught without any significant introduction to quantization, was commonly cited by students as the most difficult (and frustrating) topic in the original version of CHE 371; however, four of the nine students to complete CHE 372 (in which statistical mechanics is now covered) during the past two years identified the topic as one of the most interesting and/or important of the semester. Similar anecdotal improvements in students' attitudes toward (and understanding of) other topics have been made, particularly for other topics that were also moved from CHE 371 to CHE 372 (e.g., transition state theory).

Beyond an improvement in student learning gains, the reordering of our course content forced us to fundamentally reconsider how much time was appropriate for all of the disparate content pieces. In order to add breadth of topic coverage (especially in CHE 371), it was necessary to reduce the depth of coverage (for at least some topics); and though reducing content is often an initially difficult decision for instructors, in practice we did so without substantially diminishing student understanding of affected topics. As an example, we have reduced the time spent discussing how to determine a full set of atomic term symbols without reducing our coverage of their meaning. Furthermore, the act of relocating certain topics within the sequence has removed some redundancies from the curriculum and resulted in a reduction of necessary in-class time. Again using statistical mechanics as an example, it was (prior to the change) necessary to spend roughly 2 days of CHE 371 covering the concept and basic lessons of quantization before any useful discussion of Boltzmann distributions could be pursued. Moving the topic to a more natural place obviated the need for those class days, which could then be used for other material. Because of these time savings, we are now able to cover some topics (e.g., band gap theory) that were previously left out of the physical chemistry sequence (and the larger department curriculum) entirely and/or devote more time to others (e.g., statistical mechanics or modern directions in computational chemistry). Given that the topics that were most greatly bolstered by the reallocation of time are also among the most relevant to modern physical chemistry, the process seems like an especially worthwhile exercise.

The changes to physical chemistry have proven beneficial from the perspective of the entirety of the GAC Chemistry Department's curriculum as well. The new version of CHE 371 essentially follows the CPT's model of an effective one-semester course, and should therefore represent a vast improvement in the physical chemistry curriculum experienced by LAP/BMB majors. But in hindsight, the change also allows us to better serve ACS majors, because the new CHE 371/372 sequence provides exposure to more content than its predecessor—and the added content is itself more germane to current (and near-future) trends in the field.

Quantifying Student Learning Gains

Quantifying student learning gains is admittedly a bit more difficult from the available data. Assessment tools necessarily cover different content groupings in the two versions of the sequence. For example, before the curricular changes, questions about transition state theory were generally included in a CHE 371 quiz or exam along with topics such as basic chemical kinetics; now they are typically included in a CHE 372 exam

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 3. Comparison of Mean Exam/Quiz Scores for Selected Topics Prior to and Following Curricular Changes

Year	Mean Exam/Quiz Scores from CHE 371, % (SD), by Topic			
	QM[a]	Thermo[b]	Equil[c]	MO[d]
2009−2010	74.9 (10.4) $N = 6$[e]	67.4 (18.4) $N = 27$	67.1 (19.5) $N = 27$	64.4 (26.4) $N = 6$[e]
2010−2011	81.8 (11.0) $N = 4$[e]	75.0 (15.0) $N = 27$	64.2 (20.4) $N = 27$	64.5 (24.3) $N = 4$[e]
2013−2014	66.5 (16.0) $N = 28$	59.8 (18.4) $N = 28$	57.2 (20.9) $N = 28$	87.9 (10.8) $N = 4$[e]
2014−2015	66.5 (17.8) $N = 33$	72.6 (12.2) $N = 33$	68.2 (20.0) $N = 33$	92.3 (12.6) $N = 5$[e]
Prechange	77.0 (11.9) $N = 10$[e]	69.9 (17.7) $N = 54$	66.1 (19.7) $N = 54$	70.5 (20.0) $N = 10$[e]
Postchange	66.5 (16.9) $N = 61$	66.7 (16.5) $N = 61$	63.1 (21.0) $N = 61$	90.3 (11.4) $N = 9$[e]

[a]QM indicates topics in model quantum mechanical systems. [b]Thermo indicates topics in classical thermodynamics. [c]Equil indicates topics in equilibrium, chemical activity, and basic kinetics. [d]MO indicates topics in molecular orbital theory, approximation methods, and group theory. [e]These results indicate performance in CHE 372 rather than CHE 371.

along with more advanced concepts such as kinetic-molecular theory and reaction dynamics. While transition state theory has consistently been covered, it is problematic to quantify the impact of the curricular change on student learning about this specific topic. Furthermore, the curricular changes have been accompanied by two significant changes in assessment itself: both courses have gone from having four to five 50 min quizzes, two 50 min midterm exams, and a 2 h final exam to three or four midterm exams and a final exam per semester. Meanwhile, the exams in CHE 372 are now generally given on a take-home basis to allow students more available time/resources with which to solve more rigorous and complex problems.

Keeping these concurrent assessment changes in mind, some trends in student performance can be identified by examining two full, sequential academic years before (2009−2010 and 2010−2011) and after (2013−2014 and 2014−2015) the curricular changes. All four yearlong physical chemistry sequences were taught in full by the same instructor (this author), so there should be minimal instructor-dependent variation in student performance. Table 3 includes average quiz/exam performance for four global physical chemistry topics for which quiz/exam assessment were most (though by no means perfectly) comparable before versus after the changes. They include an introduction to necessary mathematical/statistical concepts, the historical roots and postulates of quantum mechanics and model quantum mechanical systems (referred to in Table 3 as QM); classical thermodynamics (Thermo); equilibrium, chemical activity, and basic kinetics (Equil); and molecular orbital theory, approximation methods, and group theory (MO).

Some of the notable conclusions one can draw from Table 3 include the following:

- Scores in a given course are reasonably similar in a single year. For example, Thermo and Equil were both taught/assessed in CHE 371 all four years; in 2009−2010, the exam averages for those topics (67.4% and 67.1%) were very similar. This suggests that average student performance was fairly consistent within any given class, which is to be expected because the populations are generally similar from year to year.
- The two-year averaged prechange and postchange scores for topics that were the sole purview of CHE 371 (again meaning Thermo and Equil) are also reasonably similar, each decreasing by ∼3%. The relatively small decrease suggests that CHE 371 students are performing similarly before and after the change on those topics (especially when factoring in the assessment changes), which is again expected because the profile of CHE 371 students is similar from year to year.
- In a given academic year, averages are higher—often significantly so—for CHE 372 compared to CHE 371. This is not surprising considering the populations of the two courses: students completing CHE 372 are generally a small, self-selecting, and relatively high-achieving group, typically composed of ACS chemistry majors; whereas the vast majority of CHE 371 students are LAP and BMB majors.
- Similarly, the decrease in QM performance from 2009−2011 to 2013−2015 can be attributed primarily to the relocation of that material from CHE 372 to CHE 371.
- For the one topic (MO) that was taught in CHE 372 in both versions of the course, there is a drastic increase in student performance after the change. This is surely due in part to the in-class versus take-home nature of the assessment tools, but that factor alone probably cannot account for the observed 20% increase in average exam score, especially considering the increased difficulty of take-home exams (see the Supporting Information for illustrative examples of pre- and postchange exam questions from CHE 372). As is discussed below, qualitatively similar improvements among students who completed the full CHE 371/372 sequence is the norm.

The general conclusions one draws from Table 3 are therefore that the average CHE 371 student performs rather consistently regardless of course content, and that most differences in CHE 371 performance are entirely plausible based on factors other than course content. Accepting that those conclusions are true, exposing CHE 371 students to a broader variety of physical chemistry topics at a somewhat shallower depth is a reasonable choice when considering the department-wide curriculum. Nonetheless, the individual exam grades included in Table 3 may appear to present mixed results about the efficacy of the curricular changes, and may not be seen as adequate to justify a curricular overhaul.

It is more illuminating to compare the students who completed both semesters of physical chemistry in a single academic year before and after the changes were enacted. This limits the number students being compared (eight total from 2009−2011 and nine from 2013−2015), but also makes the students more directly comparable in that each of them learned and was tested on virtually the same content over the course of two semesters; hopefully this means that they constitute a more reliable basis for comparison. To that end, the average quiz/exam scores and overall course scores for students who completed the yearlong sequence (in a single academic year, to remove the effects of a yearlong delay between CHE 371 and CHE 372) from 2009−2011 are compared to their counterparts from 2013−2015 in Table 4.

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 4. Comparison of Mean Exam/Quiz Scores and Overall Course Grade among Students Completing the Yearlong Physical Chemistry Sequence in a Single Academic Year[a]

Exam Score or Course Grade	Mean Exam/Quiz Scores and Overall Course grade, % (SD), by Year (N = 4)					
	2009−2010	2010−2011	2013−2014	2014−2015 (N = 5)	Pre-2013 (N = 8)	Post-2013 (N = 9)
CHE 371 Exam	76.5 (12.9)	75.7 (11.9)	80.5 (13.7)	80.3 (12.5)	76.2 (12.4)	80.4 (12.9)
CHE 372 Exam	70.4 (14.1)	79.0 (14.0)	87.1 (7.68)	87.8 (9.59)	74.7 (14.6)	87.5 (8.68)
Yearlong Exam	73.7 (13.7)	77.8 (13.2)	83.5 (11.8)	83.6 (11.8)	75.4 (13.6)	83.5 (11.7)
CHE 371 Course	80.5 (5.32)	82.4 (5.95)	84.9 (11.1)	85.7 (6.71)	81.5 (5.33)	85.3 (8.28)
CHE 372 Course	75.9 (5.03)	80.6 (12.5)	87.4 (7.52)	89.7 (6.36)	78.3 (9.16)	88.7 (6.54)
Yearlong Course	78.2 (5.13)	81.5 (8.70)	86.2 (9.15)	87.7 (6.05)	79.9 (6.85)	87.0 (7.09)

[a]Syllabi for all eight courses are provided as Supporting Information.

Among these students, there are two noteworthy observations. First, scores are consistent from year-to-year within the same curricular model; for example, the CHE 371 quiz/exam average is similar between 2009−2010 (76.5%) and 2010−2011 (75.7%), while the 2013−2014 (80.5%) and 2014−2015 (80.3%) averages are also similar. Second, there is an improvement of ~5% in every score following the curricular change. It is worth remembering that the overall improvement seen among the 2013−2015 students was achieved while also increasing the overall amount of content in the curriculum, especially in CHE 372. Though limited in number, the results in Table 4 suggest that students who complete the full sequence (and those most likely to have professional careers as chemists) have been performing better overall, despite being asked to learn more—and that is a very encouraging result.

DISCUSSION

It should be remembered that the decision to fundamentally change the GAC physical chemistry curriculum was initially a local solution to a local problem: the previous curriculum had some obvious shortcomings, and we wished to address them in a feasible, sustainable, and long-term way. However, the process (and outcomes) of the course redesign suggests that such changes could be broadly beneficial to the entire subdiscipline; this is suggested by Fox and Roehrig's study of the current state of undergraduate physical chemistry education,[8] which addresses several questions pertinent to the lessons we have learned in the past 2+ years of establishing our new curriculum.

Why Students Struggle

Fox and Roehrig identified what physical chemistry instructors believe to be the primary sources of student difficulty in their courses. The top four challenges they identified (and the only four to be identified by >10% of respondents) are that students struggle:[8]

- "Because they lack the necessary mathematical background" (61% of respondents)
- "To make connections between the concepts and mathematics" (33%)
- "Because they do not put forth the necessary effort" (18%)
- "To understand the concepts" (13%)

While the question of student effort is larger than can be addressed by the content of a physical chemistry curriculum alone, our changes have made positive progress on the others.

The question of mathematical background is (as indicated by the 61% response rate) a very real problem from the perspective of physical chemistry instructors. We have somewhat mitigated this difficulty in two ways. First, the use of software (e.g., Mathcad or Mathematica) as an aid for completing mathematical operations with which students tend to struggle has been conscientiously built into the new curriculum (beginning with a week-one laboratory exercise in CHE 371). This is not a new tactic,[12] but it is one that leverages the widespread availability of technology (and modern students' comfort with it) in a beneficial way. More importantly, much of the more mathematically intensive course material is now covered in CHE 372; this results in a somewhat less challenging mathematical environment for CHE 371 students. Mathematical rigor is generally less of a challenge in CHE 372, which is almost universally taken by those students (e.g., ACS majors) who already have a broader and deeper exposure to advanced mathematics due to the cognate requirements of their major. Furthermore, all CHE 372 students have had a full semester (in CHE 371) to find a level of mathematical comfort (through a combination of software and practice) before grappling with the more challenging concepts introduced in CHE 372. From an instructor's perspective, the curricular changes have been accompanied by an improvement in students' abilities to cope with underlying mathematical operations—students are better able to successfully handle the mechanics of solving problems than in prior years.

Moreover, the distribution of mathematically difficult topics has helped address the difficulties students have in making "connections between concepts and mathematics" and "understanding the concepts". The inclusion of fewer difficult mathematical principles in CHE 371 (and giving students tools for handling those that remain) allows the course to focus more on typical conceptual stumbling blocks and their connections to the underlying mathematics—in other words, it is easier to strike a more effective and mutually supportive balance between mathematics and concepts in CHE 371. The students in our new physical chemistry sequence seem to have a better grasp of the concepts (and related mathematics) than students from previous cohorts.

The Challenge of "Time"

A second difficulty in physical chemistry pedagogy identified by Fox and Roehrig deals with how the subject is taught: they report that 23% of respondents (the highest percentage of any response for this particular question) believe physical chemistry can be improved by instructors modifying their teaching strategies.[8] This appears to be in line with previously cited interest in developing new and innovative pedagogies. However, Fox and Roehrig also report that instructors state the single most limiting factor in changing teaching strategies is "lack of time" (89%).[8] Surely, the question of time has two primary facets: the amount of time an instructor has for

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

curriculum revision and development, and the amount of class time available in a given course.

Regarding course revision and development time: as suggested by Table 2, a content reorganization of the sort we have done does not necessarily require a complete overhaul of two semesters' worth of material—much of the actual content remains the same. That is, a considerable amount of the process can be accomplished through a rearrangement of one's existing notes and course structure; most of the truly necessary development comes at the edges of topics that are stitched together in a different (and often more natural) order.

The shortage of available class time is also helped by such a reorganization. This observation seems to align with results reported by Fox and Roehrig, who found that as the breadth of topics covered in physical chemistry increases, the depth at which they are covered tends to either remain the same (in thermodynamics) or even increase (in quantum mechanics).[8] As they rightly point out, "if time were a limiting factor of curricular decisions, as the breadth of topics increased the depth of topics should decrease";[8] this is what we discovered in practice. The only way to make the new sequence work was by reducing the depth of certain topics in order to increase the overall breadth of content—the primary difficulty was recognizing when we, as instructors, are devoting too much time or depth to a particular topic; it is tempting to believe that everything one covers is "necessary" content. As described above, reasonable reductions in certain content areas allowed us to reclaim a number of class days and put them to better use.

Fully acknowledging that time is a limiting factor for many faculty who are considering a significant course revision, it still may not be prohibitively time-intensive for undergraduate-level physical chemistry—particularly when weighed against the potential benefits of a redesigned curriculum.

Reconsidering the Propriety of the Traditional Two-Semester Sequence

Perhaps the most compelling reason for changing the fundamental structure of undergraduate physical chemistry is the questions of what we teach, and why. As noted above, Fox and Roehrig state that there are "similarities in beliefs of instructors regarding how similar physical chemistry courses are and should be",[8] and that "almost all [>99%] institutions represented in the survey divide physical chemistry into one semester of thermodynamics and one semester of quantum mechanics."[8] In other words, the overwhelming majority of physical chemistry instructors agree that the subject is (and should be) taught in two halves, encompassing thermodynamics and quantum mechanics, regardless of institution.

However, Fox and Roehrig also report:[8]

"[T]here was not a consistent trend for the ordering of the courses: 44% of the institutions required students to take thermodynamics first, 20% required students to take quantum mechanics first, and 36% allowed students to take the two semesters of physical chemistry in either order."

It is perhaps surprising that physical chemistry instructors so overwhelmingly agree that the quantum/thermodynamics division is appropriate, yet do so with no consensus as to the order in which the topics should be presented. This suggests that most instructors effectively view the two semesters as independent—or at the very least, independent enough that having students take them in either order is reasonably justifiable, as long as they take both courses.

This model of physical chemistry education was certainly relevant in the past—but is it still? In reality, the popular paradigm is primarily a simple reflection of the fact that chemical thermodynamics is at least half-a-century older than quantum mechanics. The chemical importance of thermodynamics was clearly recognizable by the time Pattison Muir published *The Elements of Thermal Chemistry* in 1885,[13] and thermochemistry was surely being taught in college courses by or around that time. By contrast, quantum mechanics was (according to Charles Coulson) first taught to undergraduates by Lennard-Jones as early as 1932;[14] it was still later before any textbooks relevant to chemical applications of the topic (such as Pauling's *The Nature of the Chemical Bond*[15] or Coulson's *Valence*[16]) were available. The fields of thermochemistry and quantum chemistry effectively matured independently; apparently, the manner of teaching them to college students did as well. The overwhelming majority of physical chemistry curricula continue as a tribute to that history.

However, leading edge physical chemistry research is moving in directions that rely on both thermodynamics and quantum mechanics. The physical chemistry portion of the ACS report on chemical education in the 21st century[17] identifies the importance of teaching materials that are context-rich for fields such as materials science, biochemistry, and atmospheric science; meanwhile, Fox and Roehrig report that 8% of physical chemistry instructors believe that student understanding can be improved through the use of more relevant examples and applications.[8] Such relevant, context-rich examples and applications in physical chemistry are going to come increasingly from fields such as ultrafast spectroscopy, statistical thermodynamics, computational chemistry, and mechanistic chemistry—all of which rely on both "semesters" of physical chemistry. If we are to help undergraduates understand such topics, and prepare at least some of them to engage in them in their own careers, it seems logical to teach them in a manner more reflective of our professional understanding of them. For this reason, moving beyond the historical structure of independent thermodynamics and quantum mechanics courses seems to be a timely evolution in physical chemistry education.

■ CONCLUSION

In revamping our physical chemistry curriculum, we have found that GAC students completing our CHE 371/372 sequence should now be better equipped to deal with physical chemistry-related problems than their peers from previous years. This is, in part, from better serving the population of students who only take CHE 371; but it is also in part due to a fundamental change in (and modernization of) the paradigm we use to teach them—a paradigm that is becoming increasingly relevant and important for undergraduate physical chemistry students.

■ ASSOCIATED CONTENT

Supporting Information

Sample exam questions over similar course content (specifically approximation methods and molecular orbital theory) from CHE 372 are included as a comparison of expectations before vs after the change. Syllabi for all eight courses included in Table 4 are also provided. The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00945.

CHE 372 Exam 1, Spring 2015 (PDF)

DOI: 10.1021/acs.jchemed.5b00945
J. Chem. Educ. XXXX, XXX, XXX−XXX

CHE 372 Exam 2, Spring 2010 (PDF)
CHE 371 Syllabus, Fall 2009 (PDF)
CHE 371 Syllabus, Fall 2010 (PDF)
CHE 371 Syllabus, Fall 2013 (PDF)
CHE 371 Syllabus, Fall 2014 (PDF)
CHE 372 Syllabus, Spring 2010 (PDF)
CHE 372 Syllabus, Spring 2011 (PDF)
CHE 372 Syllabus, Spring 2014 (PDF)
CHE 372 Syllabus, Spring 2015 (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

I would like to thank my colleagues in the GAC Chemistry Department, especially Amanda Nienow, for their support, encouragement, and feedback.

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