Evaluation of Chemistry 161

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Summary

• Chemistry 161, a novel course incorporating a wide range of innovative practices, many of which were informed by ideas and learning objectives gleaned from the Chemical Education community, was in the autumn quarter of 2010 with support from a Learning Technology Impact grant.

• Student engagement and satisfaction with the course's interactive format was high, with activities including feedback, discussion, and problem-solving being highly valued.

• Learning objectives for the course were expansive and evaluated with an extensive assessment program featuring pre- and post- tests, open-ended surveys, and exam performance.

• Student proficiency with algorithmic problem-solving and memorization of chemistry facts, as described by a cumulative final exam, are comparable with previous cohorts of Chemistry 161 students.

• In addition to these traditional measures, substantial gains are quite evident in conceptual understanding as assessed by using the Chemistry Concept Inventory in a pre- and post-format. Conceptual gains in selected areas are truly exceptional and the overall change clearly surpasses gains associated with standard General Chemistry instruction.

• Finally, a more sophisticated understanding of the Nature of Science consistent with the GEC learning objectives for the course is apparent for many students.

• Follow-up group interviews are planned with Chemistry 161 students. Several interwoven topics merit further attention, including a) the value of active-learning environments, b) the use of simulations and visual representations of chemical concepts, c) student epistemology and their attitude toward learning, and d) student insights into, and understanding of, scientific models.

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Class Activity Summary

Course Modifications: Computer simulations and inquiry-focused tasks were used in a technology-rich classroom in an effort to dramatically alter the traditional lecture format of an introductory chemistry course. The course (Chemistry 161), which enrolls students majoring in Chemistry, was modified in several important respects. In terms of pedagogy and instruction logistics, the traditional General Chemistry format (Chemistry 121) is taught in a lecture hall to ~150-350 students. The instructor presents a lecture via PowerPoint slides or with an overhead projector and works through example questions (see Figure 1). Students take notes and there is no group work and little chance to discuss calculations or content. There may be chemical demonstrations. In Chemistry 121 there is a weekly 45-minute recitation led by the teaching assistant. About one-third of the recitation time is used for a weekly quiz, and the rest of the time is used to discuss student questions that are often based on homework problems. Students obtain feedback of their learning at an end of unit assessment (such as a weekly quiz or a mid-term exam) or during the recitation. Laboratory assignments are poorly integrated with the rest of the class in terms of either lecture or assessment.

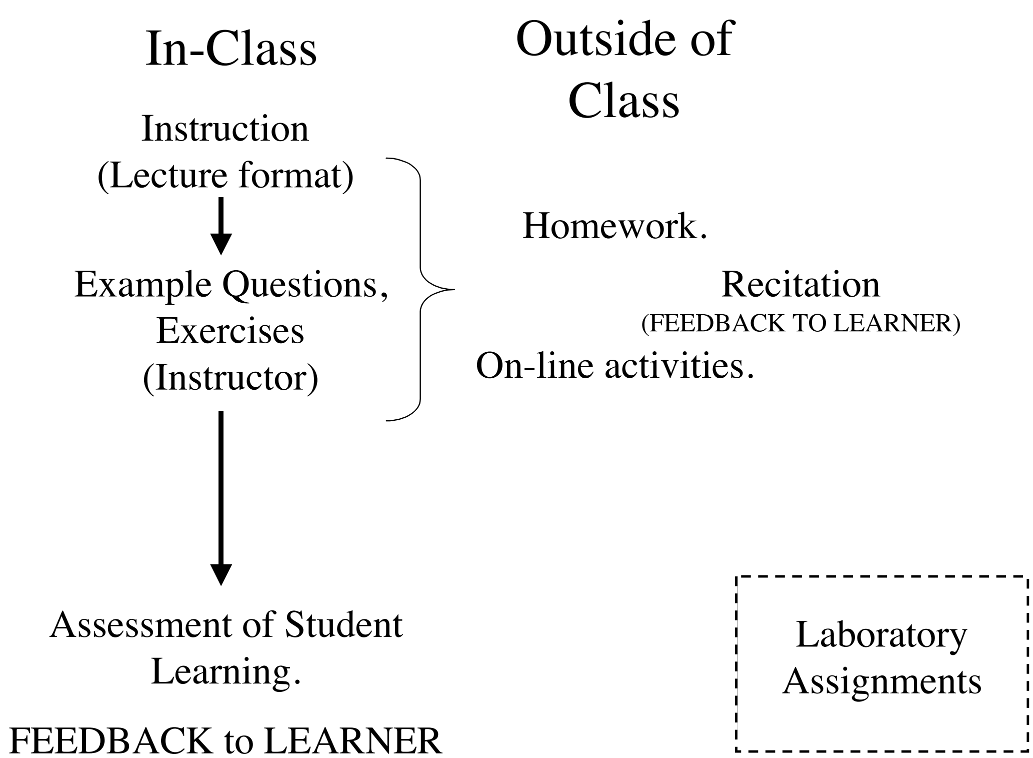

Figure 1: Outline of traditional Chemistry 121 format.

The Chemistry 161 (Autumn, 2010) course was altered to take advantage of a dramatically different classroom space in Central Classrooms that included a circular floor-plan with the instructor at the center, small tables holding 4-6 students, 36 computers that displayed the instructor's content (2 students per computer), a classroom capacity of 72 students, and white boards at the rooms periphery.

At the instructional level, Chemistry 161 was modified by 1) providing students with interactive notes that required in-class note-taking, 2) encouraging more questions and classroom discussion during the lecture, 3) including instructor-led simulations to illustrate concepts and supplement lecture. In addition, two teachers (Dr. Loza, Dr. Clark) were present at every lecture. Typically, one teacher would be the lead lecture instructor for a particular topic but both would assist with other aspects of in-class learning (Figure 2).

In-Class		Outside of Class
	Instruction: Lecture + **Interactive Notes + Discussion + Simulations + two lecturers**	
Feedback to student & **instructor**	Example Questions, Exercises (Instructor) **Questions, Exercises (Student)** **On-line questions with Mastering Chemistry** **Whiteboards**	On-line activities: **Homework, Tutorials, Quizzes** (FEEDBACK TO LEARNER)
	↓	
	Assessment of Student Learning. FEEDBACK to LEARNER	Laboratory Assignments

Figure 2. Chemistry 161 format (Fall, 2010). Course modifications vis-à-vis Chemistry 121 shown in bold.

Chemistry 161 did not have a separate recitation but instead included typical recitation activities (e.g. administering quizzes, having students work problems and receive feedback) in the lecture component of the class. Communication of student results often made use of the whiteboards. On-line tutorials or exercises were included in this active learning portion of the class via Mastering Chemistry. It should be noted that this format provided timely feedback of learning to both the student *and* the instructors in a way not possible in a Chemistry 121 course.

The outside of class activities for Chemistry 161 relied heavily on the on-line interface provided the publisher of the course textbook- Mastering Chemistry (or MC). The outside of class activities used in Chemistry 161 were not dependent on the novel Central Classroom space, however they were a significant component of the course in terms of student effort and time allocation and are an important variable to consider when describing the structure of the course.

Methodology: A post-course survey was completed by students (n=116) during a class period. Students self-reported the importance different outside of class, in-class, and laboratory activities had on their learning. They also recommended the extent to which the activities should be included in future versions of Chemistry 161. Both of these sections used a Likert 5-response format. An open-response section was also provided.

Student Views of Chemistry 161 Course Activities and Self-Reported Learning

Student views In-Class Activities

In terms of student self-reported learning, the most highly valued classroom activities were clearly 1) "having problems worked by the instructor during lecture" and 2) "working problems myself, or with classmates, during lecture" (Table 1). These related activities were identified as significant sources of learning by nearly every student. In terms of importance, the next tier of activities included "listening to lecture", "having slides or handouts to write on", "discussing content with classmates". The use of in-class simulations came next with virtually the same level of support (a fuller discussion of simulations is provided later in this document). Finally, in-class Mastering Chemistry and whiteboard activities were deemed least valuable. These data are summarized in Table 1 by ranking them according to average score. The total number of students strongly agreeing that the activity was a significant source of learning (a "5") is shown, along with the total number of students viewing the activity as neutral toward their learning (a "3"). Those in-class activities uniquely found in Chemistry 161 in comparison to Chemistry 121 are also indicated.

These data suggest that students closely (and understandably) equate "learning" with performance on assessments, like quizzes and exams, since these determine one's grade in the course. To the extent that assessments are synonymous with the ability to solve problems, their enthusiasm for such activities may be explained. It is noteworthy that Chemistry 161 provided a unique and appreciated opportunity for student-led problem solving within the lecture component of the class.

For the other activities unique to Chemistry 161, the opportunity to work in groups and discuss content with classmates was very well received. The use of in-class computer simulations was very well received by about one-third of the students. The mixed response to the simulations may be related to the fact that students were frequently passive consumers of a given simulation; it was viewed as a lecture component, not as an opportunity to "work a problem". This assessment is supported by the fact that a correlation exists between student views of simulations and their views of PowerPoint lectures, but not between simulations and working problems. In other words, the simulations are viewed as way to supplement the lecture, but not as a way to put into practice what was learned, solve a problem, and receive feedback.

An in-class activity with only modest support was the use of Mastering Chemistry (MC) during lecture. In the open-response section students voiced several common criticism, including the short amount of time allocated to the activity and the lack of feedback (not knowing if their responses were right). Mastering Chemistry may be a useful addition to the course but, to make this happen, it must be better integrated with other in-class activities. For example, students could work on a MC assignment for 20 minutes and the instructor could then lead a targeted discussion of the material; Mastering Chemistry requires a summative treatment by the instructor(s). The use of whiteboards was also novel to Chemistry 161. Based on open-response questions, it appears this activity may be improved if joined more closely with student problem-solving and discussion.

Table 1. Student views of in-class activities on learning (n=116).
A 5-point scale was used (5=the activity was a significant source of learning, 3=neutral, 1= not significant).

In-Class Activity	Specific to Chemistry 161?	Response Average	# students responding "5"	# students responding "3"
Having problems worked by the instructor during lecture.	No	4.63	81	5
Working problems myself, or with classmates, during lecture.	Yes	4.45	65	5
Having slides, handouts to write on.	Maybe	4.33	63	12
Listening to PowerPoint lecture.	No	4.09	46	19
Discussing content with my classmates during lecture.	Yes	4.13	46	16
In-class computer simulations or videos (not Mastering Chemistry)	Yes	3.80	41	33
Working on Mastering Chemistry assignments during lecture.	Yes	3.30	21	33
Sharing my work on the whiteboards during lecture.	Yes	3.35	16	48

A very intriguing question meriting further attention is the relationship between the "lecture" portion of the course and the "working of problems". Presumably, a student must first actually learn something before putting that knowledge into practice and attempting problems or exercises. Do students prefer "working problems" because they already understand the material and are looking to apply it (quite doubtful), or are they seeking to learn the material in a very, targeted, pragmatic way that may lead to a better score in the class (likely).

Overall, the student perspective of learning in Chemistry 161's novel classroom (and the in-class activities situated therein) is **extremely positive**. About **95% of students** feel that future versions of Chemistry 161 should also be taught in the Central Classrooms location, noting its special ability to increase their learning (when coupled with the activities noted above) and also promote a sense of community. Among the very few students that would like to switch to a lecture hall format, the opportunity to view in-class chemical demonstrations was a deciding factor.

Student views of Outside of Class Activities

Several outside of class Mastering Chemistry activities, in addition to more traditional outside of class learning activities, were examined in the survey. As self-reported sources of student learning, the Mastering Chemistry tutorials were viewed very positively. Although the overall view was favorable, students voiced diverse opinions regarding the optimal use of MC tutorials. For example, many students felt having "hints" available were crucial for getting them started. Others took the opposite few, holding that if the tutorial is to be done for credit then no hints should be provided. In term of time provided, students often felt the time should be extended or with no limit to increase their learning, with others feeling a narrow time limit kept them focused. It will be impossible to please everyone with the MC tutorials, but they should definitely be retained.

Table 2. Student self-report sources of learning for outside of class activities.

Outside of Class Activity	Part of Mastering Chemistry?	Avg. Score
Tutorials	Mastering Chemistry	4.21
Reading the textbook	no	4.09
Attending Office Hours	no	3.98
Homework	Mastering Chemistry	3.89
Studying with classmates	no	3.58
Quizzes	Mastering Chemistry	2.83

The use of Mastering Chemistry for quizzes was beset by many technical difficulties and many students were very negative on its continued use; quizzes should be done in class. In terms of MC homework, some students felt that it was a poor substitute for a paper and pencil version and did little to improve their retention of the material.

Student views of Laboratory Activities

The Chemistry 161 labs were the same as the traditional Chemistry 121 labs. They are expository-style verification labs in which students work independently to confirm principles they are learning. Student comments of these labs parallel those of students in Chemistry 121, often being critical of (1) the material environment ("I had to wait in line too long to use a balance"), (2) poor integration with lecture ("it would be great to match the lab of the week with the lecture") and a lack of understanding as to their purpose.

Students view most of the labs as comparable in terms of learning with two clear exceptions: Lab 1 (Measurement) and Lab 8 (Emission Spectra) are viewed much more negatively. An effort to improve the integration between lab and lecture is currently underway and this effort includes the revision of several lab experiments. Such revisions will take into account these student opinions.

It is noteworthy that incoming Chemistry majors are, in general, more welcoming of expository-style labs than are students in Chemistry 123 who have had an entire year of scripted labs such as these. The negative comments from Chemistry 161 students regarding lab experiments…"there is so much tedious work" or "labs rarely help me think through ideas, I end up following instructions like a cookbook, mindlessly", or "students are far more concerned in lab…with getting the points to boost their grade rather than understanding what it was designed to teach", or "I hoped OSU would provide more though-provoking, interesting labs than my high school. I guess I was wrong!" become the consensus when students reach Chemistry 123.

Sources of Student Learning

The student in Chemistry 161 clearly identify different sources of learning, e.g. Mastering Chemistry tutorials, working problems in lecture, attending office hours, or reading the textbook are all viewed quite positively. How do the diverse approaches relate to each other? This question may be taken up indirectly in the open-response question "Did you learn more by attending lecture or by studying outside of class?" (Course instructors would clearly answer ***both*** are needed!). Among Chemistry 161 students, 32% stated that lecture was superior, 50% identified both as sources of learning, and 18% indicated outside of class. This distribution is consistent with the fact that attendance in lecture was <u>very high</u> for the entire quarter, with more than 90% attendance rate being the norm. In contrast, the attendance in a typical lecture of General Chemistry typically ranges from 95% to 60%, depending on the lecturer, the content covered, etc. Students in Chemistry 161 are unarguably finding value in the lecture portion of the course and, perhaps most welcome of all, recognize that at the college-level in-class learning is not sufficient to master the material.

Student Views of Computer Simulations

Course Modifications: The Central Classroom space is ideally suited for use of in-class simulations. Students are at small tables with a computer being shared by every two students. Instructors in Chemistry 161 utilized this technology-rich room by having students complete tutorial assignments (through Mastering Chemistry) and making use of many media assets (Table 3).

Table 3. Media Links Posted on Carmen

Textbook Chapter	Title of Media Asset	Description	Classroom Implementation
Chapter 2	Baby & the elements	YouTube Video	Lecture supplement
	Cathode Rays & Magnets	YouTube Video	Lecture supplement
	Crookes Tube Demonstration I	YouTube Video	Lecture supplement
	Crookes Tube Demonstration II	YouTube Video	Lecture supplement
	JJ Thomson & Cathode Rays	**Interactive Simulation**	**Instructor led worksheet**
	JJ Thomson Quote	Audio Clip	Lecture supplement
	Millikan Oil Drop Experiment	Video (textbook)	Discussion/Example
	Rutherford & Radioactivity	Video (textbook)	Instructor led- worksheet
	Rutherford Scattering	Interactive Simulation	Not used in class
	Mass Spectrometer	Interactive Simulation	**Instructor led worksheet**
Chapter 4	Conductivity Caper: Terror in the Tub	Movie (instructor made)	Lecture supplement
	Electrolytes in a Cell	**Interactive Simulation**	**Instructor led worksheet**
	Conductivity of Solutions	Interactive Simulation	Instructor led worksheet
	Conductivity of NaCl	Video (textbook)	Not used in class
	Salts and Solubility	Interactive Simulation	Not used in class
Chapter 5	Carnot Cycle	Simulation	Lecture supplement
	Skate Park	**Interactive Simulation**	**Lecture supplement**
Chapter 6	Overview of Quantum Mechanics	YouTube Video	Lecture supplement
	Newton & Light	YouTube Video	Lecture supplement
	Wave Interference	**Interactive Simulation**	**Lecture supplement**
	Blackbody Radiation	Interactive Simulation	Lecture supplement
	Photoelectric Effect	Interactive Simulation	Lecture supplement
	Models of the Hydrogen Atom	**Interactive Simulation**	**Instructor led- worksheet**
	Standing Wave	Simulation	Not used in class
	Cloud Chamber	YouTube Video	Not used in class
	Multi-electron Atoms	**Simple Simulation**	**Lecture supplement**
	Standing Waves & Strings	YouTube Video	Not used in class
	Fullerene Diffraction in the Lab	Website	Lecture supplement

Activities in **bold** were examined in an end-of-class survey.

All of these media assets were either freely available online (such as YouTube videos), prepared by the instructors (e.g. an iMovie), or accompanied the course textbook (usually short videos). Interactive simulations were activities affording the user an opportunity to manipulate several variables and investigate an experiment/phenomenon. These activities were frequently used as a lecture supplement to illustrate a particular concept.

A more comprehensive use of a media asset typically involved an in-class worksheet that students completed following an instructor-led discussion.

Methodology: An end-of-class survey probing student views of seven in-class simulations (those identified in **bold** in the Table 3) was administered via Carmen and completed by 40 students. The survey provided a screen-shot of a particular simulation and asked students to identify the chemistry topics associated with the simulation, suggest why the instructor chose to include the simulation in class, and indicate whether the activity was a good use of class time and assisted in learning the content. Finally, students were asked to offer suggestions regarding the use of simulations in future courses.

Table 4. Student Views of Selected Simulations (n=40).

Simulation	Do students remember the chemistry topics? Percentage identifying correct topics in 10th week.	Do students value using the simulation? Percentage favoring the use of the simulation.
Mass Spectrometer 2nd week of class.	50% of students.	63%
JJ Thomson & Cathode Rays 2nd week of class.	82%	87%
Electrolytes in a Cell. 4th week of class.	80%	77%
Skate Park. 5th week of class.	100%	85%
Wave Interference 6th week of class.	95%	85%
Models of the Hydrogen Atom. 6th week of class.	100%	93%
Multi-electron Atoms. 7th week of class.	100%	90%

Results: When surveyed at the end of the quarter (10th week), a high percentage of student respondents (>80%) were able to identify salient topics pertinent for a given simulation in virtually every case, the one exception being a **mass spectrometer** simulation that was included in lecture the second week of class. Students were also very positive regarding the inclusion of simulations within the lecture portion of the course. Understandably, student views of the mass spectrometer simulation were the most mixed.

Student views of the **JJ Thomson & Cathode Rays** simulation, an activity in which an experiment was "conducted" to determine the charge-to-mass ratio of an electron, are representative. Instead of simply reading about the experiment or looking at a static image, the user (in the case, the instructor) manipulated experimental variables and the class recorded and analyzed the data. As one student noted, visual representations such as these "help me learn because it is something I can physically picture instead of dealing with a completely abstract topic", or as another student stated "as a visual learner, any picture helps in my retention and understanding of the material".

Simulations also provided an opportunity to go beyond traditional chemistry content instruction and include content related to the Nature of Science (NOS), such as the role of scientific models. An example of how these educational objectives may be merged is with the **Models of the Hydrogen Atom** simulation that supported the chapter on quantum mechanics. This was perhaps the most highly praised simulation in the quarter; it supported an extensive in-class discussion of spectroscopy, and also the progression from one atomic model to another, beginning with Dalton's atomic model and ending with a quantum mechanical description.

Student comments indicated that using the simulation in-class could assist with multiple learning objectives, i.e. spectroscopy content learning and improved understanding of scientific models. In terms of spectroscopy, student comments such as "This activity is very helpful!!! The energy level transitions finally made sense to me" suggest that this simulation can support such content learning in a meaningful way. In addition, numerous students valued how the simulation helped them understand different atomic models and the evidence used to move from one model to another in a way their textbook did not. For example, the simulation and accompanying discussion…

> "Helped clarify the difference between the atomic models that were not presented clearly in the book", or

> "(The simulation) showed what each scientist's experiment looked like and what results were. This could explain the problems with each", and

> "It (the simulation) enabled me to see how some of the models were more correct than others."

Finally, the activity provided a logical progression and a "story-line" that introduced the complex quantum mechanical model of the hydrogen atom. Once again, students valued the visual representation with the simulation:

> "I think this visual was successful in explaining the difference between the atomic orbital theories through a visualization that the text book simply doesn't show well."

In terms of future use of computer simulations, the overall student consensus was that such activities were valuable and well-suited for in-class implementation. Although educators often suggest having students explore simulations themselves, such use in-class is quite time intensive. These students generally agreed that simulations were beneficial when 1) the instructor took the lead to explain the simulation (and lead discussion), 2) students worked in small groups, 3) enough time was allocated to work on the task, 4) real-time feedback was provided, 5) any supporting assignments, such as worksheets, were intended to be resources to study from and not graded assignments.

Chemistry 161 in 2011: Identification of Best-Practices

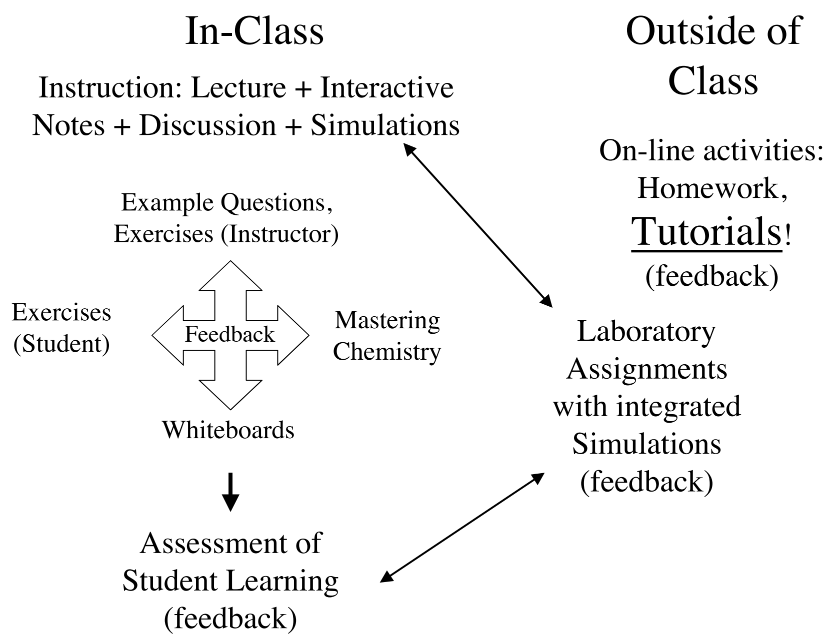

Figure 3. Chemistry 161 in 2011?

• Activities providing timely feedback, preferably in real-time, are identified by students as significant sources of learning. This should be a guiding principle for the class. Mastering Chemistry tutorial assignments completed outside of class are an example.

• In-class activities should become even more interactive and student-centered. A portion of (every?) class could be set-aside to mimic a recitation section in a well-defined manner. During this time students work on problems, show their work on whiteboards, instructors answer questions, etc.

• Lectures should continue to include interactive notes and illustrative simulations. In this setting, it is reasonable to have the instructor manipulate the simulation.

• Simulations may also be integrated into the laboratory. This might improve cohesion between class and lecture.

• The use of simulations and related activities may be useful in courses other than Chemistry 161. This possibility merits further attention.

Learning Gains Summary

Several aspects of student learning in Chemistry 161 were (and are currently being) assessed. These include student performance on a cumulative final exam that may be compared with other cohorts of students, assessment of student conceptual understanding for selected topics with a pre-, post-test evaluation, and finally student insights in the Nature of Science as evidenced by open-ended pre-, post-test questions.

Final Exam Results

Chemistry 161 used a 40 question cumulative final. Significantly, a comparable exam has been used multiple times by the lead instructor (Dr. Loza). A summary of student performance on the final exam is shown below. Analysis of historical data included paired T-test calculations for the final exam (completed at the 95% confidence level). This analysis demonstrates that:

1) All Chemistry 161 courses have outperformed the comparison Chemistry 121 course on the final exam.
2) All Chemistry 161 courses have been statistically indistinguishable in terms of performance on the final exam. The students enrolled in Chemistry 161 in Fall, 2010 did not perform differently than Chemistry 161 students enrolled in a traditional lecture format course.

Table 5. Final Exam Performance by Chapter & Topic

Chapter	# exam questions	Chem 121 (F09) Avg. score	Chem 161 (F09) Avg. score	Chem 161 (F10) am Avg. score	Chem 161 (F10) pm Avg. score
Chapter 1: Matter & Measurement	2	77%	91%	83%	85%
Chapter 2: Atoms, Molecules, Ions	3	53%	58%	73%	69%
Chapter 3: Stoichiometry	7	69%	83%	77%	77%
Chapter 4: Aqueous Reactions	4	51%	83%	89%	79%
Chapter 5: Thermochemistry	4	58%	77%	81%	83%
Chapter 6: Electronic Structure of Atoms	3	82%	89%	88%	84%
Chapter 7: Periodic Properties	2	53%	64%	73%	59%
Chapter 8: Introduction to Chemical Bonding	7	69%	79%	82%	74%
Chapter 9: Molecular Geometry Bonding Theories	8	51%	66%	73%	65%

Table 6. Overall Final Exam Performance.

Topic	Chapter	Chem 121 (F09)	Chem 161 (F09)	Chem 161 (F10) am	Chem 161 (F10) pm
Metric Conversion	1	81%	96%	88%	87%
Significant Figures	1	72%	86%	78%	82%
Isotopes	2	49%	40%	73%	62%
Ionic Formula	2	64%	72%	76%	73%
Nomenclature	2	47%	61%	69%	73%
Balancing Equations	3	96%	100%	99%	98%
Stoichiometric Conversion	3	91%	98%	100%	100%
Types of Reactions	3	39%	57%	52%	46%
Types of Reactions	3	35%	49%	34%	37%
Empirical Formula	3	94%	99%	99%	95%
Stoichiometry	3	58%	83%	69%	80%
Stoichiometry- Limiting reactant	3	61%	93%	85%	86%
Net Ionic Equations	4	69%	76%	81%	80%
Reduction-Oxidation Reaction	4	73%	74%	91%	66%
Solution Concentration	4	88%	95%	96%	91%
Stoichiometry and Solutions	4	69%	85%	87%	80%
Specific Heat Calculation	5	78%	94%	93%	93%
Bomb Calorimeter	5	40%	65%	69%	71%
Application of Hess' Law	5	54%	72%	84%	91%
Application of Hess' Law	5	58%	75%	76%	78%
Bohr Model Calculation	6	97%	99%	99%	100%
Periodic Trends	7	78%	82%	96%	82%
Electron Configuration	6	59%	72%	97%	53%
Electron Configuration	6	91%	95%	69%	98%
Identification of an Acid	7	27%	46%	49%	36%
Ranking of Lattice Energy	8	40%	37%	46%	40%
Valence Electron Trend	8	77%	86%	90%	76%
Lewis Symbol	8	75%	85%	90%	78%
Partial Charges	8	56%	74%	75%	69%
Resonance Structure	8	76%	87%	87%	80%
Lewis Structure	8	75%	88%	91%	80%
Bond Energy Calculation	8	84%	94%	93%	96%
VSEPR Geometry	9	59%	83%	85%	80%
VSEPR Geometry	9	55%	59%	54%	71%
VSEPR Geometry	9	65%	86%	81%	91%
VSEPR Geometry & Polarity	9	55%	58%	60%	58%
Hybrid Orbitals	9	53%	74%	69%	76%
Hybrid Orbitals	9	53%	80%	78%	78%
Molecular Orbital Notation	9	22%	26%	25%	16%
Molecular Orbitals & Bond Order	9	42%	58%	55%	46%
AVERAGE		**64%**	**77%**	**77%**	**75%**

The cumulative final exam employed here is comprehensive. It is an excellent example of an exam that evaluates student understanding of content traditionally associated with General Chemistry in a manner consistent with its presentation in the course textbook and is well-matched for a traditional chemistry lecture course. The data here strongly suggests that students enrolled in the active-learning Chemistry 161 course ***do not*** under-perform (or over-perform) students enrolled in a traditional lecture-based Chemistry 161 course. This is noteworthy. Significant class-time in Chemistry 161 (Fall 2010) was dedicated to learning objectives not evaluated on the final exam. For example, student conceptual understanding of chemistry and their insights into the Nature of Science were recurring themes that did not appear on the final exam. Student exposure to topics like spectroscopy and the development of scientific models was extensive, as evidenced by the expansive use of media assets (simulations, movies, etc., see above) when discussing Chapter 6. The final exam, however, under-weighted such content. The fact that students in Chemistry 161 (Fall 2010) did not under-perform a comparable lecture course (with a cumulative final exam tailored to such a learning environment) is encouraging if student learning in these other areas occurred.

Conceptual Understanding of Chemistry

A dominant theme of chemical and physics education for the last several decades has been the failure of traditional instruction to address student shortcomings in terms of conceptual understanding of scientific content (Nakhleh, 1992). The identification of student alternate conceptions (also known as misconceptions) has been the focus of countless of studies and such investigations are currently "the face" of modern chemical education (Gabel, 1999). It has been repeatedly advocated that chemical instructors **must** address student deficiencies in this area by modifying their instructional emphasis. The Chemistry 161 course described here is an initial attempt at OSU to take these calls to action seriously.

Methodology: Selected portions of the Chemical Concept Inventory (CCI) were used in a pre-test, post-test format. The test was administered in-class both times and so the response rate was very high (n=99). A series of open-response questions were also included. The CCI is an established and validated instrument with wide-spread use at the high school level, at universities, etc. (Mulford and Robinson, 2002). The modified CCI version employed here examined student understanding of chemical reactions, physical changes, particle descriptions of matter and stoichiometry, bond energetics, the size of atoms, thermochemistry, saturated solutions, and properties of atoms. A defining characteristic of concept inventories is that they probe understanding in a non-algorithmic manner; it is not sufficient to memorize how to do a calculation, but rather the underlying principle must be understood. Traditional chemistry exams usually assess memorized processes or definitions, not understanding. Balancing equations, writing formulas, unit conversions, solving stoichiometry problems, determining concentrations, identifying a phase change, writing quantum numbers, writing Lewis structures, identifying molecular geometries are all considered by chemistry education researchers as memorizable processes.

Overall CCI Results

Student performance for pre- and post- CCI tests are shown in the Table 7 and Figures 4 and 5. As points of comparison, in addition to pre- and post- data for Chemistry 161 (Fall 2010) the following cohorts are included in the table: CCI pre-test data for Chemistry 121 (Fall 2008), pre- and post- data collected during the CCI validation in 1st year General Chemistry, and pre- and post- data for high school teachers that participated in an intensive 3-week professional development workshop focused, inter alia, on alternative conceptions in chemistry.

How to interpret all of these numbers? While examination of this data set will continue, here are a few preliminary observations:

1) Pre-test data indicate Chemistry 121 and Chemistry 161 students, like their counterparts at other institutions, have many chemical misconceptions when entering General Chemistry. Chemistry 161 students perform a little better than other General Chemistry students; high school teachers perform much better.

2) Chemistry misconceptions are only changed when the instruction targets them. Alternative conceptions in chemistry (all chemical educators agree) are highly intractable and difficult to modify. **Very significant improvement** occurred for Chemistry 161 students and workshop participants, with virtually no improvement for students experiencing traditional chemistry instruction (see Figures 4 and 5).

3) **Post-test scores for Chemistry 161 students are much higher than General Chemistry students** for all topics included in Chemistry 161. The topic of saturated solutions was not included in Chemistry 161 and performance on this question showed no improvement. This suggests that classroom pedagogy in Chemistry 16 led to the learning gains.

4) The normalized gains for Chemistry 161 students are outstanding for two questions: the size of atoms (Q. 4) and bond energy (Q. 5). Both of these topics received direct instruction using a pedagogical approach akin to "intervention texts". Such an approach forces students to first reflect on the deficiencies in their initial understanding before replacing it with a more scientifically acceptable view. The topic of bond energy was taken up many times during the quarter in novel ways, such as with an interactive simulation and as an activity featuring students using magnets, so such gains are especially rewarding.

5) Questions 7 through 10 all address misconceptions related to thermochemistry. Chemistry 161 gains in this area are modest and trail those of the workshop participants, suggesting that it may be helpful to incorporate activities from the workshop in future versions of Chemistry 161.

Table 7. Chemical Concept Inventory (CCI) Data.

	Question Topics	121 Pre avg (N~550)	CCI Validation Pre avg. (N=928)	CCI Validation Post avg.	CCI Validation gain**	**161 Pre avg. (N~100)**	**161 Post avg.**	**161 gain****	Teachers Pre avg. (N~20)	Teachers Post avg.	Teacher gain
1	Reactions and chemical terms.	39	36	30	-0.094	**46**	**61**	**0.278**	71	72	0.000
2	Boiling water, physical change	32	40	47	0.116	**43**	**60**	**0.298**	75	88	0.520
3	Formulas, particles, stoichiometry	16	11	20	0.101	**18**	**34**	**0.195**	56	71	0.341
4	Size of atoms	N/a	25	32	0.093	**25**	**57**	**0.427**	37	41	0.063
5	Properties of atoms	N/a	19	25	0.074	**17**	**33**	**0.193**	31	47	0.232
6	Bond energetics	N/a	28	30	0.028	**39**	**60**	**0.344**	31	41	0.145
7	Thermochemistry	31	51	46	-0.102	**51**	**49**	**-0.041**	50	71	0.420
8	Thermochemistry	28	N/a	N/a	N/a	**35**	**49**	**0.215**	44	65	0.375
9	Thermochemistry, Heat transfer.	N/a	N/a	N/a	N/a	**38**	**33**	**-0.081**	44	47	0.054
10	Thermochemistry, Heat transfer,	N/a	N/a	N/a	N/a	**14**	**17**	**0.035**	38	35	-0.048
11	Saturated solutions*	34	32	34	0.029	**35**	**25**	**-0.154**	N/a	N/a	0.000

*This question is a "control" since the material was not covered in Chemistry 161.

**Normalized gain = (post score – pre score) / (points possible – pre score)

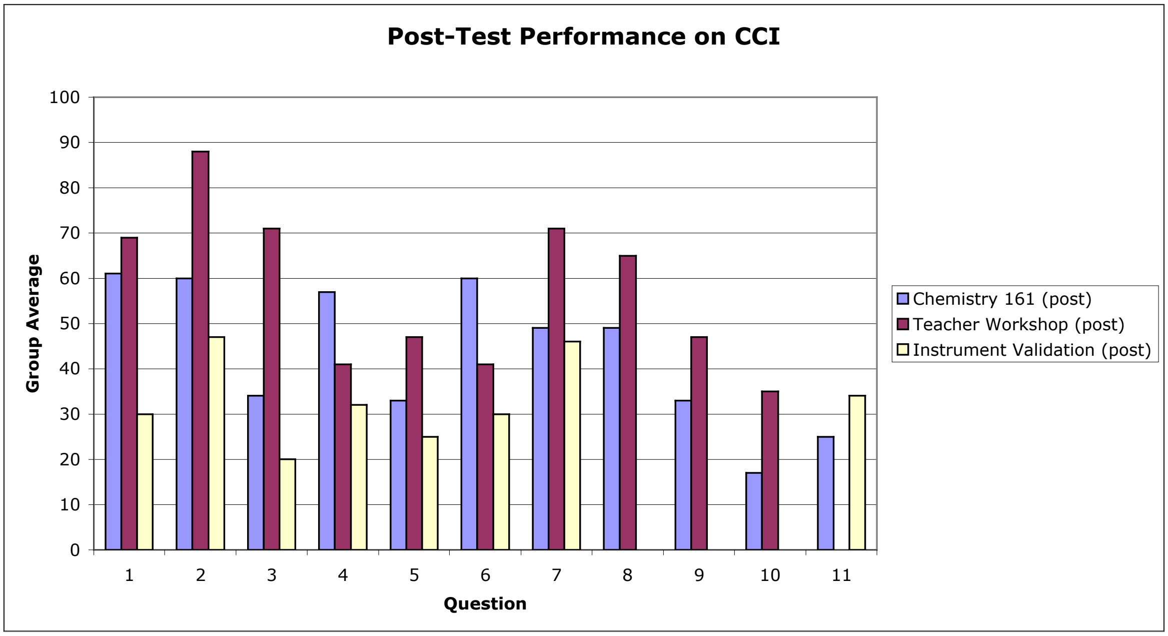

Figure 4. Comparison of Post-Test Performance on the CCI. Note, question 11 (saturated solutions) was not included in Chemistry 161.

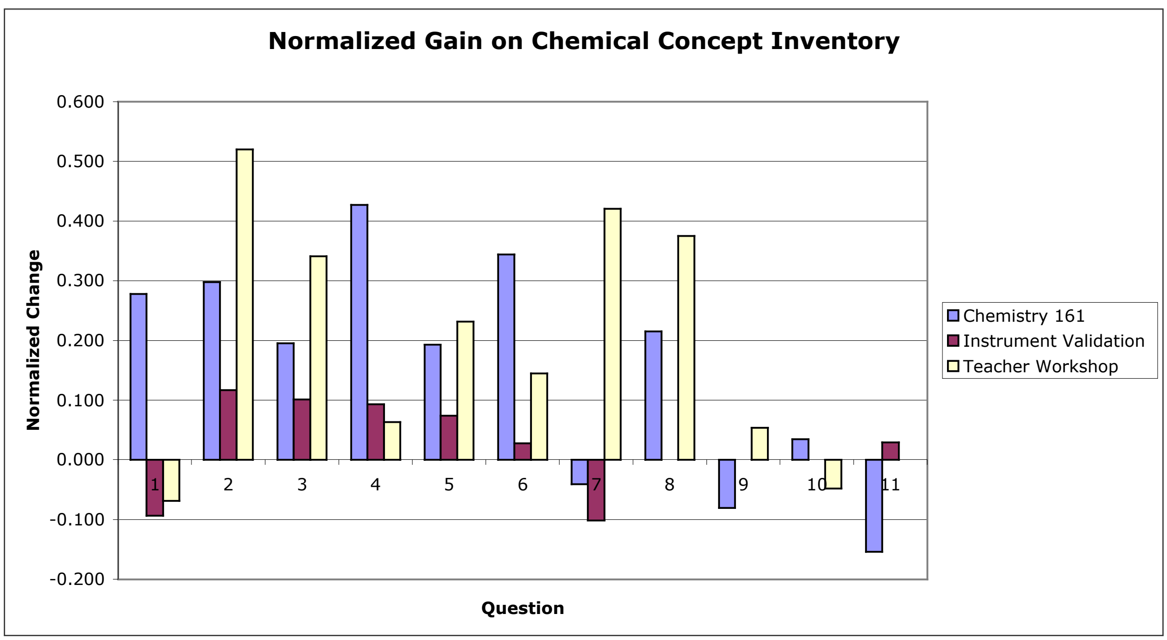

Figure 5. Normalized Gains on the CCI for Chemistry 161 students, General Chemistry students during CCI instrument validation, and teachers attending a professional development workshop. Normalized gain = (post score – pre score) / (points possible – pre score)

Conceptual Understanding- Insights from Open Response Questions.

In addition to standard multiple-choice CCI questions, open-response questions were employed (usually in a pre-, post- format) to examine student understanding of specific topics including electrolytes, effective nuclear charge, atomic structure, and chemical bonding. A detailed investigation of these responses is underway, but a few initial observations are possible

Chemical Bonding. A central theme unifying the topics in Chemistry 161 (or Chemistry 121) is chemical bonding. Early chapters contrast molecular and ionic substances, then the topics of atomic and electronic structure, effective nuclear charge, and electronegativity precede an examination of bonding theories as concepts such as Lewis structures, ionic and covalent bonds, bond energies, VSEPR geometry, and finally molecular orbital theory conclude the course. To probe student understanding of these topics the following open-response question was used on an end of class survey (a pre-test was not used):

> "In nature atoms are almost always found bonded to other atoms. **What** is a chemical bond and **why** do atoms form chemical bonds?"

The target knowledge communicated in Chemistry 161 is consistent with other General Chemistry courses (Taber, 2004) as students are shown the importance of electrical attractions and repulsions, taught about hydrogenic atomic orbitals, quantum numbers and associated rules (Aufbau, Hund, etc.), molecular orbitals, atomic orbital hybridization, molecular orbitals being formed by overlap of atomic orbitals, and delocalization in systems like benzene.

Students in Chemistry 161 are able to recite the basic tenants of chemical bonding and about one-quarter of the final exam targeted this material (see Tables 5 and 6). However, like other General Chemistry students (Taber, 2004), the Chemistry 161 students hold fast to an alternate conceptual framework for discussing bonding, i.e. that atoms form bonds to obtain full electron shells rather than as the outcome of physical forces. This "octet" framework has been shown to be tenacious and persists even when more advanced models are presented. Students repeatedly view chemical processes, not as due to forces acting between charges, but as a being driven by the "needs" of atoms.

As shown in Table 7, very few Chemistry 161 students do more than describe (in simplest terms) ionic or covalent bonds when asked to discuss a chemical bond, i.e. a chemical bond is the "transfer or donation of electrons", or "the sharing of electrons". Less than 10% of the students mention electrical attractions or repulsions of any kind, and only one student mentioned the overlap of orbitals (!). The student's rationale for why bonds form (Table 8) is entirely consistent with the alternate conception described by Taber, i.e. atoms are motivated to satisfy an octet.

Table 7. “WHAT is a chemical bond?” (N=94, multiple response possible)

Response	Number of responses
Ionic Description: Transfer or donation of electrons.	53
Covalent Description: Sharing of electrons.	65
An electrostatic attraction, charged particles.	7
An attraction (no details provided)	5
Metallic bonding mentioned (no details provided)	4
Involves overlapping orbitals	1

Table 8. “WHY are chemical bonds formed?” (N=94, multiple response possible)

Response	Number of responses
Greater stability, related to a noble gas configuration, satisfying the octet rule, or filing a valence shell.	33
To obtain a noble gas configuration, satisfy the octet rule, or fill a valence shell as an end in itself. No mention of “stability”. Often stated in terms of what an atom “wants” or “desires”.	20
To be more “stable” (no details provided).	18
Stability discussed in terms of lower potential **energy.**	7
Electrostatic attraction and stability	4

Student understanding of chemical bonding has been investigated extensively by chemical educators (Teichert and Stacy, 2002; Ünal, 2006; Boo, 1998; Coll and Treagust, 2002; Nahum, 2007; Acar and Tarhan, 2008; Doymus, 2008; Coll and Taylor, 2002; Taber, 2004; Özmen, 2004; Barker, 2000; Taber, 2002) and Chemistry 161 students' views are very similar to other General Chemistry students, favoring a “naïve realism” description of chemical bonds (Talanquer, 2006).

The “motivation” for atoms to have an octet framework often includes anthropomorphic language such as “*the goal of atoms* is to have a full shell, like the noble gases”, or “a chemical bond is when two atoms react with each other *hoping to either gain or lose an electron*” (italics added). This teleology has been shown to be very common and is a prevalent misconception with students (Talanquer, 2006). Chemistry 161 students often mentioned “stability” that accompanies chemical bonds as being important but less than 10% discuss this stability in terms of energy and only about 5% identify stability with electrostatic attractions, leaving in doubt what the students really think when mentioning stability. Finally, several students hold elements themselves must not be stable since they form bonds (“many elements are not stable by themselves in nature”, “not every element is stable when alone”, “most elements are unstable”).

Why should these chemical bonding misconceptions be addressed? Researchers have shown that the alternative conceptions identified here (common to Chemistry 161 students and General Chemistry students alike) are an impediment to later learning; once the alternate scheme is established, the student finds it difficult to appreciate bonding that is intermediate to ionic and covalent bonding (polar bonds) or falls outside of this framework (e.g. metallic or hydrogen bonds). Indeed, the subsequent challenges that students face in Chemistry 122 regarding intermolecular forces are intrinsically linked to these alternate conceptions.

How should these chemical bonding misconceptions be addressed? As described above, Chemistry 161 students dramatically improved their understanding of energy (see Figures 4 and 5, question 6 on the CCI) when instructors used tested strategies discussed in the chemical education literature, especially the work of Teichert and Stacy (2002). Given the extensive chemical education work in this area, Chemistry 161 and Chemistry 121 students and instructors would benefit from a similar approach and should give the identified best practices a try.

Atomic Structure & Student Insights into the Nature of Science

Instructors for Chemistry 161 took very seriously the GEC goals and learning objectives stated for first-quarter General Chemistry. The applicable GEC Learning Objectives for the course are that 1) students understand the basic facts, principles, theories and methods of modern science; 2) students learn key events in the history of science; 3) students provide examples of the inter-dependence of scientific and technological developments; 4) students discuss social and philosophical implications of scientific discoveries and understand the potential of science and technology to address problems of the contemporary world. The definition and role of scientific theories was a recurring theme and was often supported by illustrations from the history of science. The social implications of science and the interplay between scientific discoveries and the contemporary world were frequently addressed in lecture with everyday examples of "General Chemistry" brought to the students' attention via newspaper headlines, news videos, etc.

The GEC learning objectives, as is common for science courses at OSU, are part of what is commonly termed the Nature of Science (or NOS). The Nature of Science is an important learning objective for science courses, is included in science teaching standards in Ohio, and is a central theme of science education research (a review article on the subject (Lederman, 1992) has been cited close to 1000 times!). Yet, by any measure, its treatment in traditional General Chemistry courses is virtually non-existent. For example, it is commonly stated that chapters 1-4 in Chemistry 121 are predominantly review and that OSU students should arrive with an understanding of this material and so a cursory treatment is warranted. Such an attitude is short-sighted since this content provides rich material to draw from when discussing NOS and, if it is indeed "review", the students will benefit from having a greater comfort level of the chemistry content while learning NOS concepts. Among science educators "there appears to be an almost universal commitment…to promote the goal of student understanding of the nature of science" (Smith & Scharmann, 1999), yet such commitment has not translated into explicit inclusion of this material in General Chemistry courses (certainly not at OSU).

Understanding NOS is a key component of scientific literacy (AAAS, 1989) and, although a single definition of the nature of science is problematic, and much debated (Alters, 1998; Eflin, et al., 1999), there is currently agreement that science is a human endeavor reliant on empirical observation and subject to change, and that such a conception of science should be conveyed to students and science educators (Mathews, 1998). Researchers have also convincingly demonstrated that students *do not* improve their NOS understanding in a traditional science class or even in an authentic research experience without direct instruction and reflection on NOS topics; it is not enough to simply "talk about science" - the customary practice in science courses, with the implicit assumption that students will somehow come to learn NOS content on their own.

The pre-test probed student initial understanding of the NOS. One topic was student understanding of scientific laws versus scientific theories. Student ignorance of this topic neared 100% as everyone expressed the view that theories were ill-defined and a preliminary step leading to a law ("theories grow up to be laws when more data is collected). This is a very prevalent misunderstanding and pointed to the need for direct instruction. Such direct instruction was emphasized beginning the second week of class.

As shown in Table 3, many media assets exist to support the discussion NOS as it pertains to Chapter 2 (atomic structure), and these were incorporated into the lecture and revisited again in Chapter 6 (electronic structure of atoms). Many historical examples were given to illustrate the development of scientific theories and models, such as experimental investigations of cathode rays with supporting videos, simulations, worksheets and discussion. Simulations were also used extensively when discussing quantum mechanical concepts and wave behavior (McKagen, Perkins, et. al., 2008) and a lengthy discussion describing different models of the hydrogen atom employed a simulation (McKagen, 2008). To examine whether this extensive affected student views the following pre- and post-test question was asked:

> "Using words and/or drawings communicate your current understanding of the atom's structure. How certain are scientists about the structure of the atom? What specific evidence, or types of evidence, do you think scientists used to determine what an atom looks like?"

The intention here was to probe both changes in student insights into NOS topics (such as the role of scientific models, the nature of scientific theories, creativity in science, the relationship between evidence and inference, the tentativeness of scientific knowledge, the manner in which scientific theories change and develop, etc.) and to probe student understanding of quantum mechanical ideas since this question asked students to comment on their own understanding of the atom's structure. In contrast, the original Views of Nature of Science instrument (VNOS-C) has a similar question but provides this content-specific information (Abd-El-Khalick, 1998).

Student responses were coded to identify changes between their pre- and post- views. Resulting themes were 1) did student views of the atom become more deterministic, e.g. electrons in orbitals analogous to planets in orbit around the sun, or more probabilistic; a conceptual shift of this kind is viewed as crucial to understanding basic quantum concepts (Papaphotis and Tsarpalis, 2008; Tsaparlis and Papaphotis, 2009; Petri and Niedderer, 1998), 2) did the students identify historical evidence or experiments used to describe atomic structure, and was such evidence correctly described or interpreted by the student, and 3) did the student response communicate improved insights into the NOS, especially regarding scientific models.

Table 9. Pre- to post- changes in student views describing atomic structure (N=93).

Response	Number of Occurrences
More probabilistic description of the atom, such as an electron cloud, mention of Heisenberg Uncertainty principle, or wave description of an electron.	40 times
More deterministic description of the atom, such as electrons in orbits.	3
Increase in relevant scientific evidence or experiments, such as Rutherford's gold foil experiment or cathode rays.	45 (In 8 instances the student interpretation of the results are incorrect)
Increased understanding or mention of the role of models.	21
No clear change	22

As shown in Table 9, student post-test responses indicate considerable change as gains occurred in all three areas (more probabilistic interpretation, better understanding of historical evidence, improved insights into NOS). Preliminary coding of student responses indicates that about 10% of the Chemistry 161 students had gains in all three areas, 25% had gains in two of the areas, and 40% had gains in one of the areas, leaving only 25% with no apparent change.

Representative students responses are shown in Table 10. An example of a student with gains in all three areas is student #1. Before the course the student recognized that different models existed for describing electrons, but they held that the position of electrons was ill-defined because they were "moving too fast" (a frequent comment). This viewed matured into a probabilistic interpretation with experimental support, including spectroscopic data, and a clearer description of how scientific models change.

Table 10. Selected student pre-, post student responses describing atomic structure (1=Hurley, 2=Oster, 3=Blay, 4=Hawi, 5=Davis)

	Pre-course	Post-course
1	In the center of the atom are protons and neutrons which are much larger than the electrons. There are several different ways an atom can be thought of. One has orbitals and shows electrons in fixed spots based upon what the element is. This, however, is imperfect as electrons are always moving and so a field of probable locations is also used. I am not really sure how scientists determined these things.	A nucleus is at the center of each atom and is made up of protons and neutrons. Electrons surround the nucleus and their position is a probability with clouds where electrons are likely to be. Scientists have used trial and error in determining the atom's structure. Different models include the billiard ball model and plum pudding model, among others, and each model has improved on the one before based on things like the gold foil experiment and examination of emission spectra.
2	I have absolutely no idea how the structure of an atom was objectively examined. All I remember is that an atom is a particle of matter that makes up, fundamentally, the world around us.	All theories of an atom's structure are theories, not laws, so the structure is not definitely proven but scientists operate on the current model because it hasn't been disproven. Scientists used electronegativity and the cathode ray tube experiment to disprove the previous models, such as the plum pudding model. By shooting molecules at an atom they observed a concentrated nucleus that deflected them and only once in a while would allow one to pass- the opposite was hypothesized.
3	The atom has a nucleus (core center). Sometimes has a membrane. Scientists are certain of the atom. They have studied if for many years. Scientists took observations from the microscopic level and studied them at the macroscopic level.	There are $6.02\text{x}10^{23}$ atoms in one mole. Scientists have made many models for the atomic structure. Atomic model- Rutherford, Plum Pudding Model. Electrons have a dense nucleus.
4	The atom is a microscopic ball. Scientists are not very certain about the structures of atoms because they have not seen what they look like.	An atom is a tiny circular particle that is not visible to the human eye. Each atom contains a certain number of electrons and, and protons, but only one nucleus. Scientists are uncertain about the structure of an atom. Scientists based their evidence on what atoms look like when they brought two atoms close together.
5	Scientists are very certain about the structure. They used very powerful microscopes. (Student includes sketch of an electron in orbit around the nucleus).	Scientists are positive about the structure of the atoms (sketch of electron in orbit). All different tests have been performed but super microscopes have been the best way to seen an atom.

Student #2 illustrates the complexity that accompanies student understanding of this material. The student begins with a very poor understanding, but clearly progresses and attempts to describe the role of experimental evidence and how it informs/changes scientific models (with some success). They are confused, however, about specific experimental results (e.g. the conclusion of Rutherford's gold foil experiment is correct but the results are described incorrectly).

Student #3's comments show confused the initial understandings may be as the initial description of nucleus pertains to a cell, not an atom! Although this seems incredible, such confusion is not unheard of (Taber, 2002). The post-course response is a listing of facts or ideas but does not communicate an understanding of the content.

Student #4 begins with a very elementary view of how science knowledge moves from experimental data and observation to inferences, theories and models. For this student, seeing is believing; a scientist cannot be certain of something if they have not directly observed it. This view is little changed during the quarter and scientists remain uncertain about the atom's structure because they have not directly witnessed, although paradoxically the student seems to imply that scientists have observed what two atoms are joined together!

Finally, student #5 also illustrates the very elementary view of scientific knowledge, this time concluding that scientists are quite certain of atomic structure because they have actually witnessed atoms with "super powerful microscopes". Although the student seems to be aware of other experimental evidence in the post-course assessment, it is the use of microscopes that is most convincing to this student. Many students on the pre-test cited microscopes as principal experimental evidence for the atom's structure. Such "powerful microscopes" were not discussed in the class, however, and so students favored other forms of evidence on the post-survey. This student, however, holds fast to the idea that microscopes are most important and fails to appreciate the abstractness of atomic models.

The wide range of student insights in NOS among Chemistry 161 students parallels the wide range of chemistry knowledge for these students, but the two are not correlated. Gains clearly occurred for many students, however, and important strategies for incorporating NOS instruction and assessment have been tried for the first time at OSU. These are valuable initial steps. It would be prudent to build on these efforts and consider inclusion of best practices (both teaching and assessment) in Chemistry 121…it is assumed that students are currently learning some NOS material in Chemistry 121, yet we are neither teaching or evaluating it.

CONCLUSIONS

Chemistry 161 was a radically re-designed General Chemistry course that included many dramatic changes in terms of 1) in-class learning environment, 2) classroom pedagogy, 3) outside of class activities, 4) course learning objectives, and 5) course evaluation.

Regarding points 1 & 2, the novel classroom setting facilitated a learning environment that was quite interactive, encouraged frequent feedback from the instructor, included small group work and student discussion, and provided a heightened use of technology such as computer simulations, videos, tutorials, etc. This technology often featured a high level of interaction and visualization. As described in the Class Activity Summary portion of this document, students held a very positive view of those portions of the class that provided real-time feedback with "working problems" being highly valued. In a traditional General Chemistry course such activities are typically confined to a recitation led by a teaching assistants; students in Chemistry 161 benefited by having an instructor lead interactive activities, discuss and demonstrate approaches to problem-solving, etc.

The outside of class activities focused on Mastering Chemistry assets. Those activities that provided students with feedback and practice, such as tutorials, were viewed very positively. Outside of class activities are an important part of the course, given the wide range of student background knowledge upon entering the course.

Learning objectives for Chemistry 161 were significantly expanded from the typical Chemistry 121 course and included a) traditional algorithmic content learning and memorization of chemistry content, b) addressing student misconceptions and conceptual learning associated with non-algorithmic problems, and c) increasing student insights into the Nature of Science. Expansion of learning objectives in this manner coincided with an effort to align the course with best practices identified by the chemical education community.

Diverse instruments were used to assess student-learning gains in Chemistry 161. The overall evaluation is quite positive; the future of Chemistry 161 is very bright and the potential for a truly innovative experience is self-evident. By traditional measures, such as the cumulative final exam, student performance in Chemistry 161 meets the standard set by previous cohorts of Chemistry 161 students, suggesting student proficiency of traditional learning objectives. Significantly, overall gains in conceptual learning (as measured by selections of the Chemical Concept Inventory) were outstanding and clearly exceeded gains associated with traditional General Chemistry instruction. In fact, on selected topics, Chemistry 161 gains were remarkable even when compared with other programs specifically designed to address alternative conceptions in Chemistry (e.g. a teacher education workshop featuring modeling instruction). Some topics, however, merit further attention as improvement was modest, especially thermochemistry and student conceptualization of chemical bonds.

Student insight into the Nature of Science was probed in the context of student learning of atomic structure. The topic of atomic structure and the electronic structure of the atom comprised about one-fourth of the quarter's content. Treatment of these topics was supported by a host of novel in-class practices including an expanded discussion of the role of evidence and historical experimental data, the development of models, and scientific decision-making, with a variety of media assets (videos, simulations) being used. Student gains in this area were noteworthy, especially regarding conceptual change away from a deterministic view of electronic structure. An increased student understanding of the role of scientific theories and models was also suggested by end of course open-response questions; this point will be probed with student interviews.

Overall satisfaction with the courses was quite high, with about 95% of students recommending future versions of the course having a similar framework. The use of computer simulations was also well received, with an approval rating of about 80-85%.

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