# Perspectives of Chemists: Tracking conceptual understanding of student learning in chemistry at the secondary and university levels

Kathleen Scalise[c], Jennifer Claesgens[b], Rebecca Krystyniak[a], Sheryl Mebane[a], Mark Wilson[c], Angelica M. Stacy[a,b,d]

[a]Department of Chemistry, UC Berkeley [b]SESAME Graduate Group, UC Berkeley [c]School of Education, UC Berkeley [d]Lawrence Hall of Science, UC Berkeley

**Abstract:** ChemQuery/Living by Chemistry (LBC) is a chemistry curriculum and assessment project that has framed the "big ideas" of chemistry in order to provide developmental cohesion and promote conceptual understanding for students. This framework, called *Perspectives of Chemists*, informs on patterns and characteristics of the "conceptual change space" in the domain. The framework is based on integrating conceptual change theory with National and California State Science Standards, expert opinion, teacher interviews and classroom observations. The *Perspectives* framework has now been used to analyze progressions of student understanding at the high school and university level. This presentation will present data and analysis from this study, and show how articulation across the scale allows tracking of conceptual change pathways over time.

**Objectives**

Currently, much of general chemistry content, at the high school and university levels, is taught and assessed in terms of facts, algorithms and procedural knowledge without emphasizing conceptual understanding (Hesse & Anderson, 1992, Nurrenbern & Pickering, 1987; Phelps, 1996). The instruction usually focuses on covering a breadth of topics without a consistent emphasis on integrating across concepts. For example, a typical high school chemistry course might group learning into a dozen or more separate topics, such as stoichiometry, atoms and elements, the periodic table, chemical bonding, molecular structure, ideal and real gases, acid-base equilibrium, solubility, oxidation-reduction reactions, thermochemistry, chemical kinetics and thermodynamics. Students are taught many discrete knowledge pieces without an emphasis on coordinating this knowledge into a functional whole. "Big ideas" are often lost in the wealth of material presented. The emphasis on rote learning and algorithms assumes that students' procedural knowledge translates and/or supports the development of conceptual understanding. (Nurrenbern & Pickering, 1987; Phelps; 1996, Sawrey, 1990). However, typical chemistry instructional organization does not promote conceptual understanding in most students (Hesse & Anderson, 1992; Bodner, 1991; Driver 1994). Students with procedural knowledge often do not realize that the equations learned in chemistry for problem solving can be understood in terms of fundamental ideas that form the basis of the discipline (Gabel, 1987).

In response to these concerns, the National Standards, along with many other reform efforts, have called for a shift in the emphasis of science education from memorization of facts and procedures to a deeper understanding of the subject matter. This focus on learning for understanding is grounded in the theory of conceptual change to explain how learners achieve conceptual understanding by connecting concepts, experience, and strategies (Smith, diSessa, & Roschelle, 1994; Strike and Posner, 1992).



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

The purpose of the ChemQuery/Living by Chemistry project is to bring conceptual change theory into practice in the teaching and learning of chemistry. To this end, the project proposes a model for instructional material and assessment development based on an organizing framework of core chemistry concepts.

**Assessment models**

Typical assessments in chemistry classes are made as people-to-people *comparisons* with no clear mapping to the discipline (norm-referenced). We know where particular students fall relative to one another, but we lack an understanding of where each student fits on a scale of higher order thinking in the discipline. The learning can only be described in comparison to other students but does not describe the understanding of chemistry that is developing among the students. This method of making unlinked measurements in order to monitor student learning is in stark contrast to measurement strategies used by scientists. For example, when talking about the weather, the day can be described as warmer than previously (a norm-referenced comparison). Or, we could develop a *model* about what factors influence weather, and then use the model to decide on what *variables* to measure (e.g., temperature, pressure, etc.). For each variable, we can define a *scale* for measurement (e.g. degrees Celsius or atmospheres). Once there is a scale for each variable in the model, we can design *instruments* for tracking changes in weather (e.g., a thermometer or a barometer). This measurement strategy is referred to as a criterion-referenced measurement.

The LBC/ChemQuery assessment system is based on a criterion-referenced measurement that tracks student learning by making *people-to-discipline* measurements that assess student understanding to chemistry domain concepts. Specifically, we are developing a *model* that organizes the overarching ideas of the discipline of chemistry into a framework from novice levels of understanding to graduate and expert levels, which we refer to as the “Perspectives of Chemists”. The purpose of the framework is to describe a hierarchy of chemistry content that then defines *variables* to allow us to measure learning outcomes, determine *scales* for these variables, and construct an *instrument* for measuring the values of these variables for individual students, calibrating the instrument using item response theory (IRT) psychometric models, with which fit, validity, and reliability are estimated. While we expect other frameworks for chemistry readily could be proposed and perhaps validated, our purpose was to attempt to describe, build and validate at least a single framework to test the approach.

**Variables: The Perspectives of Chemists**

The LBC/ChemQuery assessment framework, the *Perspectives of Chemists*, is built on the theoretical conception that the field of chemistry can be largely grouped into 4 core concepts: matter, change, stability, and uncertainty. The purpose of the proposed perspectives is to provide a coherent assessment “frame” that mediates between the level of detail in chemistry courses and overarching ideas, The intent is to use these perspectives as measurement variables to map student progress. The aim is to define what knowledge students need in order to build understanding in chemistry. The proposed “big ideas” of chemistry are described in Table 1. The first three will be described further below; the fourth has not been well defined at this point.



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

Table 1: The four proposed variables.

| *Perspectives* of Chemists | |
|---|---|
| **Matter** | Matter is composed of atoms arranged in various ways. |
| **Change** | Change is associated with the rearrangement of atoms. |
| **Stability** | Stable substances only undergo change with energy input. |
| **Uncertainty** | This perspective is under development, It will relate to quantum models. |

**Matter.** The *matter* perspective is concerned with the composition, structure, properties, and amount of matter. The focus is on the electrons and how they are positioned in order to cause attractions between atoms and restrict their motions.

**Change.** The *change* perspective is concerned with the type of change, the progression of change, and conservation of matter involved in change. The focus is on the exchange, combination and recombination of atoms, ions, and groups of atoms.

**Stability.** The *stability* perspective is about inferring whether a system will remain stable or change will take place, and considers the possibilities, influences and effort involved in stability. As we have worked through developing and validating this framework, we are currently working on this variable and so far had found it more difficult to describe than the matter and change perspectives. In some ways, stability could be included in matter and change as "why" questions. Why does the substance exist? Why did change occur? However, since energy considerations are a major perspective of chemists, we think this needs to be defined as a separate variable. Stability provides a link between matter and change by beginning to define what the possible configurations of the system are (a link to matter) and what effort is required to change it (a link to change).

Within the LBC/ChemQuery assessment system, these proposed *Perspectives* define the variables to measure student learning gains within the domain of chemistry. While there are certainly other ways to divide the discipline of chemistry into overarching ideas, the usefulness of the approach is only realized when the details for a chosen set are worked out and supported by empirical evidence. This set of perspectives was chosen, an instrument constructed (a set of questions to assess student understanding), student responses gathered, and the components of the measurement system refined over several iterations, as evidence was collected to analyze the framework model.



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

**Scale: Levels of student understanding**

Within each of the Perspectives, a scale to describe student understanding was proposed, see Table 2. The levels within the four proposed variables are constructed such that students are required to give more complex and sophisticated responses to increase their score from describing their initial ideas in Levels 1-3 (Notions), to relating the language of chemists to their view of the world in Levels 4-6 (Recognition), to formulating connections between several ideas in Levels 7-9 (Formulation) to fully developing models in Levels 10-12 (Construction) to asking and researching new questions in Level 13-15 (Generation***).***

Table 2. Levels of proficiency within three of the Perspectives variables.

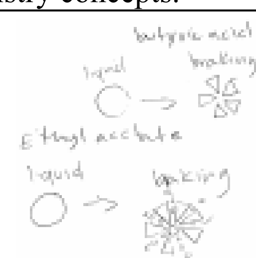
| **Levels** (low to high) | **Matter** | **Change** | **Stability** |
|---|---|---|---|
| **1-3 Notions** | What do you know about matter? (initial ideas, logic, real world knowledge) | What do you know about change? (initial ideas, logic, real world knowledge) | What do you know about stability? |
| **4-6 Recognition** | How do chemists describe matter? | How do chemists describe change? | How do chemists describe stability? |
| **7-9 Formulation** | How can we think about interactions between atoms? | How can we think about rearrangement of atoms? | How can we think about the direction of change? |
| **10-12 Construction** | How can we understand composition, structure, properties and amounts? | How can we understand type, progression, and extent of change? | How can we understand possibilities, influence and effort affecting direction of change? |
| **13-15 Generation** | What new experiments can we design to gain a deeper understanding of matter? | What new reactions can be designed to generate desired products? | What new metastable materials can we synthesize? |

As a specific example, consider the matter variable. A sample question, the scoring guide, and examples of student work are given below, see Figure 1. In Levels 1-3 (Notions), students can articulate their ideas about matter, and use prior experiences, observations, logical reasoning, and knowledge to provide evidence for their ideas. The focus is largely on macroscopic (not particulate) descriptions of matter, since students at this level rarely have particulate models to share. In Levels 4-6 (Recognition), students begin to explore the language and specific symbols used by chemists to describe matter. The ways of thinking about and classifying matter are limited to relating one idea to another at a simplistic level of understanding, and include both particulate and macroscopic ideas. In Levels 7-9 (Formulation), students are developing a more coherent understanding that matter is made of particles and the arrangements of these particles relate to the properties of matter. Their definitions are accurate, but understanding is not fully developed so that student reasoning often is limited to causal instead of explanatory mechanisms, such that one phenomenon is described as related to or sometimes "causing" another, but no route, or mechanism, is able to be put forward as supporting evidence of the relationship. In their interpretations of new situations students may overgeneralize as they try to relate multiple ideas and construct formulas. Since the responses in the sample question were obtained from students near the beginning of high school chemistry, even the best students had not reached Levels 9-11 (Formulation) where they are expected to relate the arrangements of atoms with properties for instance, however we are currently collecting evidence from more advanced university-level students in these levels. In Levels 10-12 (Construction), students are able to reason using normative models of chemistry, and use these models to explain and analyze the phase, composition, and properties of matter. They are using accurate and appropriate chemistry models in their explanations, and understand the assumptions used to construct the models. In Levels 13-15 (Generation), students are becoming experts as they gain proficiency in generating new understanding of complex systems through the development of new instruments and new experiments.

**Figure 1. Sample Problem and Scoring Guide**

"You are given two liquids. One of the solutions is butyric acid with a molecular formula of $C_4H_8O_2$. The other solution is ethyl acetate with the molecular formula $C_4H_8O_2$. Both of the solutions have the same molecular formulas, but butyric acid smells bad and putrid while ethyl acetate smells good and sweet. Explain why you think these two solutions smell differently."

| | | |
|---|---|---|
| | 0 | **Response**: "I have absolutely no idea."<br>**Analysis**: Response contains no information relevant to item. |

| | | |
|---|---|---|
| **Notions** | 1 | **Response**: "Just because. That doesn't seem possible. How can they be different when they have the same molecular formula?"<br>**Analysis**: Student makes one macroscopic observation by noting that the molecular formulas in the problem setup are the same. |
| | 2 | **Response**: "Using chemistry theories, I don't have the faintest idea, but using common knowledge I will say that the producers of the ethyl products add smell to them so that you can tell them apart."<br>**Response**: "Just because they have the same molecular formula doesn't mean they are the same substance. Like different races of people: black people, white people. Maybe made of the same stuff but look different."<br>**Analysis**: These students use ideas about phenomena they are familiar with from their experience combined with logic/comparative skills to generate a reasonable answer, but do not employ molecular chemistry concepts. |
| | 3 | **Response**: "Maybe the structure is the same but when it breaks into different little pieces and changes from liquid into gas they have a different structure in the center and have a different reaction with the air. (Shows drawing:)<br><br>**Analysis**: This answer acknowledges that chemical principles or concepts can be used to explain phenomena. Attempts are made to employ chemical concepts based on a "perceived" but incorrect |

| | | |
|---|---|---|
| | | understanding of chemistry in the first example and solely employing chemical jargon in the second example. |

| | | |
|---|---|---|
| **Recognition** | 4 | **Response**: "I think these two solutions smell different is because one chemical is an acid and most acids smell bad and putrid while the ethyl acetate smells good and sweet because its solution name ends with "ate" and that usually has a good sweet smell."<br>**Analysis**: This response correctly cites evidence for the difference in smells between the two chemicals, appropriately using smell combinatorial patterns taught in class and chemical naming conventions, but does not explain the root cause as the difference in molecular structure between the two chemicals. |
| | 5 | **Response**: "They smell differently b/c even though they have the same molecular formula, they have different structural formulas with different arrangements and patterns."<br>**Analysis** This response appropriately cites the principle that molecules with the same formula can have different structures, or arrangements of atoms within the structure described by the formula. However it shows an incomplete attempt to use such principles to describe the simple molecules given in the problem setup. |
| | 6 | **Response**: (Begins with problem setup below, showing molecular formula of labeled butyric acid and same formula labeled ethyl acetate**.)**<br>$C_4H_8O_2$ - butyric acid $C_4H_8O_2$ - ethyl acetate<br>"The two molecules smell differently because the have different molecular structures. The butyric acid contains a carboxylic acid structure (which smells bad) and the ethyl acetate contains an ester (which smells good). We can tell which molecule will smell bad and which will smell good by studying the molecular structure and by looking at the names. Any 'ACID' ending name will smell bad and any '-ATE' ending name will smell good."<br>**Analysis**: Response cites and appropriately uses the principle that molecules with the same formula can have different structures. Student correctly cites rule learned in class pertaining to smell patterns in relation to functional groups identified by chemical name, and uses this information to begin to explore simple molecules. However, student stops short of a Level Three response, which could be made by examining structure-property relationships through, for instance, presenting possible structural formulas for the two chemicals and explaining the bonding involved. |

Advancement through the levels is designed to be cumulative. In other words, students measured at a Level 5 are expected to be able to describe matter accurately and use chemical symbolism to represent matter. This is essential before they can begin to relate descriptions of matter with an atomic scale view in Levels 7-9. Our evidence to date shows that students enter high school chemistry at Level 1-3 (Notions), and that they are between Levels 6 and 7 (between



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

Recognition and Formulation) after one year of college-level chemistry. Levels 13-15 (Generation) are not expected to be reached until in most cases graduate school.

**Method and Results**

With these preliminary instruments, we have analyzed patterns of student responses using item response theory (IRT) psychometric models. The scores for a set of student responses and the questions were calibrated relative to one another on the same scale (a "logit" or log of the odds scale) and their fit, validity, and reliability estimated. These scores were matched against the LBC/ChemQuery "Perspectives" framework describing levels of success in chemistry from the novice high school student up through the expert.

The *same* assessment questions were used to map student performance in chemistry at two different levels of study, high school and university level. The same open-ended questions as those given on post-tests at the end of one year of instruction to 420 high school students (academic year 2002-03) were administered to 116 first year university students at the University of California, Berkeley (June '02) after they had completed college level introductory chemistry and were beginning organic chemistry. Both groups of students were assessed on two of the variables described above, Matter and Change.

Since these were open-ended questions scored by human raters using scoring rubrics, or guides, as discussed above, it is important to consider the impact of rating on student scores. The effect size of inter-rater comparisons of scoring were found to be on average ±0.5 on a scale of 1 to 15, meaning that on average having one rater rather than another would move a student's score about one-half level on the 1-15 scale. The 15-point scale measures student understanding from entering high school chemistry through graduate school. Student fit across the instrument was also reasonably good, with about 85 percent of the students scoring consistently across items.

On the 15-point Perspectives scale, high school students averaged 3.5 (0.7 Standard Deviation) on Matter and 3.4 (0.7 SD) on Change. This can be compared to the average score of 4.6 (0.7 SD) out of 15 on both Matter and Change for the college freshman, who had completed college general chemistry as well as usually one year of high school chemistry. The distribution of students on the Matter variable can be seen in Figure 2.

Interpreting these scores qualitatively, after one year of high school and one year of college chemistry, UC Berkeley students in the sample population measured on the framework in the range of *Recognition* of basic science models of matter and change, with some students beginning to move to a sound conceptual understanding of multirelational interactions between atoms, and the generation of accurate causal mechanisms. Many students still overgeneralize as they try to relate multiple ideas and engage in problem-solving, so students at this level would not be expected to effectively construct many models predicting composition, structure, properties and amounts of matter. Most of the students are building a sound basis for future development, however a minority of about 5 percent, even after achieving acceptable grades in two years of chemistry instruction, remain firmly conceptually ensconced in macroscopic misconceptions that seem likely to hinder future development of their ideas in science. An additional 40 percent consistently answer basic introductory conceptual chemistry questions with inaccuracy or incompleteness.

High school students in the sample population were found to be moving from a "notions" conception — based on macroscopic views of matter and real-world knowledge rather than a particulate view —toward simple normative models of chemistry that describe and explain matter at a particulate level. These students can articulate their ideas of matter, and use prior experiences, observations, logical reasoning and real world knowledge to provide evidence for their ideas. Many are beginning to relate numbers of electrons, protons, and neutrons to elements and mass, and the arrangements and motions of atoms to composition and phase. However, following instruction, lower achieving students consistently generate answers focusing on macroscopic rather than particulate descriptions of matter, and, for higher achieving students, ways of thinking and classifying matter are limited to recognizing simple definitional concepts and representations. Chemistry concepts are rarely related, or used to build on each other, and "invented" chemistry notions — often molecular concepts used out of scope — were a prominent feature of the majority of student answers in the sample population.

A more detailed analysis of the distinctions we are finding between the different levels of student responses follows. For example, when asked the following question:

> It is often stated that carbon atoms (C) tend to form 4 bonds. Is this statement true for $CH_2O$ (formaldehyde)? Provide evidence to support your thinking.

At the notion level students respond that this cannot be because there is only 2 H's and 1 O, not 4 things. As they move to recognition student responses site rules of HONC 1234, referring to 4 valence electrons and/or drawing Lewis dot structures but are remaining unable to apply them correctly to show how double bonds can form. This can be thought of as overgeneralization, without understanding the limits and/or basis for the rule. Most students at the high school level fall into this level of understanding in the framework. However, as students progress to more sophisticated levels of understanding this general rule becomes more dynamic. They can apply their understanding of bonding rules to include double bonds. At this point they are correctly relating rules of bonding to explain observed substances. Here we are find many of the University level students after completing introductory chemistry. Higher levels of conceptual understanding would include ideas of why carbon tends to form 4 bonds based on VSEPR or Molecular Orbital theory, which are examples of what we describe as explanatory models.

While matter and change score means were the same in the university level population and only slightly higher on matter than change for the high school population, it should be noted that nearly a quarter of students had scores on matter and change that differed significantly by at least one score level. Consistently higher proficiency on one variable over another may indicate where particular students need to focus study attention. Also, preliminary results suggest there may be "ordering" of the difficulty of content *within* variables. For instance on the Matter variable, the wide range of questions that asked about the *composition* of matter, or in other words what it is made of, were found to be consistently easier for students than *structure* questions — how molecules are arranged relative to each other. More investigation is taking place on these ordering effects.



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

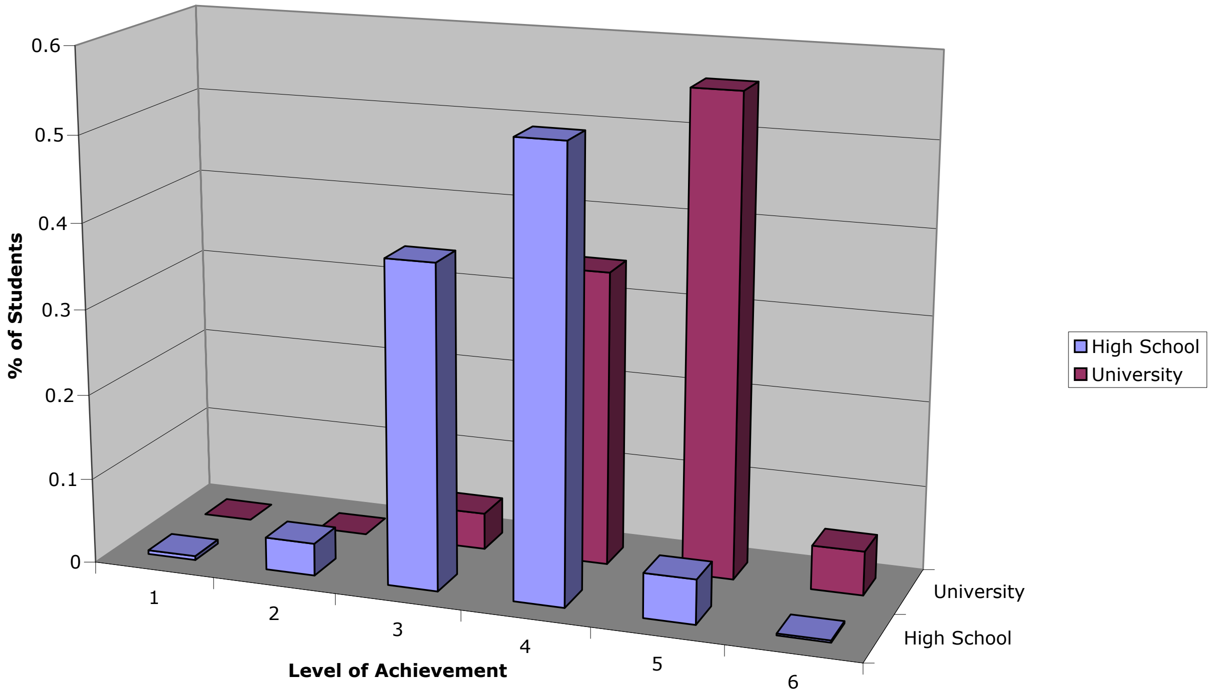



Figure 2. Level of Achievement on Perspectives Framework by High School and University students in the LBC/ChemQuery sample.

**Conclusion**

This preliminary pilot study shows how a generalizable conceptual framework calibrated with item response modeling can be used to understand and track student conceptual change in chemistry over time. Learning within the first Perspective was shown to be measurable as a progressive continuum, with student learning conceived not simply as a matter of acquiring more knowledge and skills, but as progress towards higher levels of competence as new knowledge is linked to existing knowledge, and deeper understandings are developed from and take the place of earlier understandings. This is in contrast to a traditionally much more fragmented view of the discipline in which students often fail to integrate their knowledge, and are unable to "reason like a chemist" when problem solving.

After one year of high school and one year of college chemistry, UC Berkeley students in the sample population measured on the framework in the range of recognition of basic science models of matter, with some students beginning to move toward understanding multirelational interactions between atoms. Higher performing students were able to generate accurate causal inferences, although still overgeneralizing while relating multiple ideas, while about 5 percent of students even after two years of achieving adequate grades in chemistry instruction, continued to rely on a macroscopic rather than particulate view, and exhibited substantial concrete misconceptions similar to those observed in the high school population. An additional 40 percent consistently answered conceptual questions with inaccuracy or incompleteness.



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu

High school students in the sample population were found to be moving from a "notions" conception — based often on macroscopic observations and real-world knowledge rather than normative chemistry models — toward a particular view of matter. Some had achieved an accurate but simplistic particulate view of matter, while others continued to rely on macroscopic concepts and invented chemistry. None were yet relating multiple ideas as seen in the college population.

In addition to the studies described here, more in-depth longitudinal studies are now underway to follow students at multiple time points throughout the year, compare responses on open-ended and closed-ended item designs, and to describe trajectories of learning through the conceptual change space described by the *Perspectives* framework. Also, at the university level, data has been collected for students halfway through the completion of organic chemistry.

**References**

Brown, A. L. (1992). Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Setting. *The Journal of Learning Sciences* 2(20) (pp 141-178).

Claesgens, J., Scalise, K., Draney, K, Wilson, M., and Stacy, A. (2002). *Perspectives of chemists: A framework to promote conceptual understanding of chemistry.* Paper presented at the annual meeting of the American Educational Research Association, New Orleans.

Hesse, J. & Anderson, C.W. (1992). Students Conceptions of Chemical Change. *Journal of Research in Science Teaching* 29 (3) (pp277-299).

Phelps, A. (1996). Teaching to Enhance Problem Solving.: It's more than just numbers. *Journal of Chemical Education* 73(4) (pp301-304).

Smith, J.P., diSessa, A. & Roschelle, J. (1993). Misconceptions Reconceived: A Constructivist Analysis of Knowledge in Transition. *The Journal of the Learning Sciences* 3(2) (pp 115-163) Mahwah, NJ: Erlbaum.

Strike, K.A., and Posner, G.J. (1992). A revisionist theory of conceptual change. In R.A. Duschl and R.J. Hamilton (eds), Philosophy of science, cognitive psychology, and educational theory and practice. (p 147-176). Albany, NY: State University of New York Press.

Strike, K.A., and Posner, G.J. (1982). Conceptual change and science teaching. *European Journal of Science Education*, 4(3), (pp 231-240).



Contact: Professor Angelica M. Stacy, astacy@socrates.berkeley.edu