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TEACHER CONCEPTIONS AND THE CURRICULUM:
A LONGITUDINAL, MULTICASE STUDY OF
COLLEGE CHEMISTRY TEACHING

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Curriculum and Instruction

by
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December, 1997

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ACKNOWLEDGMENTS

Many people contributed to the completion of this work and I would like to thank them for their efforts.

I first wish to express my sincere appreciation and gratitude to the members of my dissertation committee, Dr. Ron Good, Dr. Jim Wandersee, Dr. Catherine Cummins, Dr. Spencer Maxcy and Dr. Bill Stickle, who encouraged and supported my research at every step along the way.

I particularly want to express my gratitude to Dr. Ron Good, who, while challenging me to undertake a difficult study, also offered his guidance, wisdom and endless amounts of patience throughout. I could not have had a better major professor.

Four chemistry professors and a considerable number of students were involved in various aspects and phases of the research and their participation made the study possible. Unfortunately, these individuals must remain anonymous.

I am also indebted to several friends and colleagues who preceded me in various graduate programs and who offered support and suggestions based on their own doctoral experiences. Pat, Bobby, Mic and Joanna, thank you.

Finally, there is really no way to adequately express my gratitude to my wife and children, except perhaps to say that due to your patience, perseverance, and support, my graduate work is now at last completed.

PREFACE

In a 1993 editorial appearing in the *Journal of Research in Science Teaching* (JRST), Ron Good discussed the many forms of constructivism (1993, p. 1015). He emphasized the importance of trying hard to make clear what we mean and to identify our biases at the outset. This preface is written in response to the need for clarity and definition when discussing constructivism and related topics.

Clark (1988) and others have pointed out that science teachers have a philosophy of science - a set of theories or beliefs about the nature of scientific inquiry, of scientific knowledge and reasoning, and science learning. Often these conceptions have been somewhat implicit, often acquired unreflectively along with the content knowledge in science classrooms. Indeed, this notion lies at the center of a research tradition which holds that teaching behaviors are guided by and make sense in relation to a personally held system of beliefs and knowledge. This conceptualization of teaching contrasts with the earlier process-product paradigm that focused on teaching behavior, but which was curiously devoid of references to teacher knowledge, particularly of subject matter content. But if teachers have a philosophy of science and science education, what might it consist of and how might it relate to science teaching practices, particularly at the college level?

The traditional perspective in college science has incorporated beliefs in the continuous, linear progress of science, of the empirical, deductive scientific method and in the immutability of scientific fact (Grandy, 1997). It has also often included a conception of science teaching which is termed didacticism. With its behaviorist underpinnings, didactic teaching is supported by a facts

before thinking model of learning which assumes learners possess no significant knowledge which could have a bearing on the learning process prior to a teaching episode. As a science teaching method, it emphasizes telling, practicing and may incorporate conventional, standardized approaches to testing.

When teachers first encounter constructivism, it is usually presented as a superior philosophical and pedagogical alternative to didacticism. Advocates of constructivism often suggest it is key to reforming science education. Whether or not constructivist teaching models will fulfill this role remains to be seen. But it is important to understand how constructivism might or might not relate to these efforts. There are several points to consider. First, as a learning theory, constructivism has empirical support from cognitive and educational research. It incorporates a major principle of cognitive psychology – that learning occurs as a result of the active "construction" of ideas through a process which links prior knowledge with new. It also suggests that teachers need to be aware of representational and motivational dimensions that can restrict or promote student learning. This may not be easily done, and the resulting set of tasks will likely be greater than those required for traditional teaching.

However, both constructivism and didacticism are frequently expanded beyond educational theory into the realms of philosophy and epistemology. For example, it is frequently assumed that a realist or objectivist epistemology is associated with traditional, didactic pedagogy, while a non-realist philosophy is linked with constructivism. This is not necessarily the case. Scientists and science educators who may understand science in an objectivist way, may adopt a constructivist perspective on science teaching and learning without adopting a non-realist philosophy. Nola (1997) goes further by suggesting that the

philosophical debates concerning objectivist and radical constructivist accounts of the nature of knowledge (i.e., scientific realism vs. non-realism) can do little to inform or reform the pedagogical enterprise. They may in fact further confuse efforts to do so.

A second point concerns the application of constructivism as a learning theory to classroom teaching. I have borrowed Clement's (1993) term "guided constructivism" to describe teaching in conceptual chemistry - an approach somewhere between didactic and discovery methods, and perhaps representing some of the pragmatic limitations of constructivist principles applied in large, entry level college classes. As this study will demonstrate, the classes were, in fact, structured to the extent that content topics were selected and sometimes didactically introduced by teachers. Teaching strategies, however, were frequently interactive and designed to draw out students' prior knowledge and engage their reasoning ability as a way to promote conceptual understanding. Arguably, teachers in both the traditional and conceptual classes would claim conceptual understanding as a teaching objective in chemistry. But in the traditional classes this was closely identified with the act of problem solving which, of itself, only implies a functional understanding of concepts and principles.

By contrast, in conceptual chemistry, a functional understanding meant that students could think and reason with theoretical concepts in different contexts. The capacity to do so was acquired only when students during explanations or problem solving could go through the steps of reasoning themselves and make explicit the reasons for a correct answer. Using the constructivist metaphor, the students had "constructed" a knowledge of chemistry in the process.

These objectives reflect different conceptions of teaching – conceptions based upon quite different perspectives on how students learn and how subject matter content should be taught (for purposes of this study, a teacher's understanding of how to teach introductory college chemistry is distinguished from an understanding or knowledge of the content itself, which was presumed to be equivalent among the teachers). Yet, if college science teaching has been as disappointingly ineffective for a majority of students as the studies suggest, efforts to reform practice must also address teachers' conceptions and ways to promote desired change. Domain-specific models may help teachers better distinguish between didactic and constructivist pedagogical alternatives in the classroom and their potential effects in promoting student learning, engendering positive attitudes and reducing attrition from science courses.

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ABSTRACT

Strategic innovations and interventions to reform college science teaching will be required to promote the retention and achievement of those students who might otherwise elect to defect at the entry-level courses. The extent to which this can be achieved will depend upon educational research into ways that the science curriculum can be restructured to accomplish the dual function of enhancing science literacy while promoting recruitment to scientific careers.

To explore these issues, four introductory college chemistry classes were observed over a period of two years. The classes were designated either as traditional or conceptual. Selection into these categories was based upon recorded differences in prior student attrition rates and selected curriculum characteristics. The research consisted of a comparative, interpretative account of factors associated with these differences and focused on teacher conceptions, classroom teaching and testing practices, and student learning outcomes in an enacted chemistry curriculum.

Data were collected from classroom observations, structured and unstructured interviews, researcher-constructed tests and survey instruments, and course and department tests and records. Teacher classroom instruction and interviews were recorded, transcribed and coded to detect emerging themes. The findings of this longitudinal, multicase study are as follows:

- 1) Teachers who taught the traditional chemistry classes held a conception of teaching that was consistent with didactic accounts of student learning and how subject matter should be taught. The

conceptions of teachers who taught the conceptual chemistry classes were more consistent with constructivist perspectives.

- 2) Teacher conceptions were linked to consistent differences in the way chemistry content was organized, represented and tested in the course curriculum.
- 3) The results of individual student interviews suggest that students who took the conceptual chemistry classes may have been better able to recall, recognize and apply chemistry theoretical concepts than the traditional students.
- 4) The class-level performance of conceptual students equaled the traditional students on both research based tests and conventional, multiple-choice, final examinations. They also exhibited significantly more positive attitudes, and their course completion rates far exceeded their traditional counterparts.

CHAPTER 1

INTRODUCTION

The following appeared in the May 1991 issue of the Journal of Chemical Education:

A week prior to graduation at a major American university, twenty-five seniors selected at random, were asked a single question: What is the difference between an atom and a molecule? Only a third of the students queried could answer the question correctly... (p. 392).

In the authors' view, this result serves to illustrate that many students in American colleges and universities today complete their formal education without gaining an understanding of even the most fundamental concepts of science (Hazen and Trefil, 1991). With increasing numbers of scientifically illiterate graduates emerging from our secondary and post-secondary institutions, science educators, administrators, and policy-makers are calling for major reforms of the American system of science education (AAAS, 1989; NSF, 1988).

Kenneth C. Green's 1989 report entitled A Profile of Undergraduates in the Sciences cites evidence that there has been a fundamental change in undergraduate science majors during the last 25 years. For example between 1966 and 1988, the proportion of college freshmen planning to major in science and mathematics fell by half. Unfortunately, the high defection rates among aspiring science majors are not offset by recruitment from nonscience fields. High defection rates also are seen in the discipline-oriented training of secondary school science teachers. A disconcertingly small number of science and mathematics majors report plans to pursue careers as secondary science teachers. Higher

education administrators and science faculties, left with their traditional responsibilities for maintaining their institutions' capacities for research, teaching, and services, are facing a system of science education that appears no longer able to attract and retain students in disciplines widely believed to be critical to the nation's future (NSF, 1988).

The entry-level science courses taught in colleges and universities are pivotal features in science education. They greatly influence the career choices of students who aspire to scientific careers and provide an important basis for their future scientific and professional studies. They also often represent the culminating science courses for many nonmajors and, as such, can play an important role in establishing scientific literacy and developing positive attitudes toward science (Tobias, 1990).

However, Gregory (1992) notes that such courses are apparently of poor instructional quality. Her concern appears well-founded considering the current high defection rates and the small percentage of college graduates who meet the standards for scientific literacy defined by the National Science Teachers Association.

Hewitt and Seymour (1991) conducted a three-year survey of factors bearing upon decisions of science undergraduates at four-year colleges and universities to switch to nonscience majors. Complaints about teaching and difficulties in obtaining help with academic problems were identified by some 89% of the students surveyed. Complaints about teaching also were reported by more science majors than any other type of problem. Students focused on the personal attributes and pedagogical style of teachers rather than their knowledge of science content. Apparently, the majority of

students who chose to switch out of science majors do so for pedagogical reasons based on their experiences while enrolled in science courses. Why should this be the case? Some studies suggest that science teaching, unlike research, is not seen as the work of science. Research takes both an intellectual and professional priority over teaching for many faculty. Other factors also are seen to play a role. Entry-level science classes typically have high student/faculty ratios which make the faculty inaccessible to all but a few students. Adequate resources may not be made available to such courses which are often viewed as barriers to protect the more advanced courses from all but a few select students. However, whatever the reasons for the persistence of traditional teaching practices, it is clear that for all too many the delivery of college science instruction is viewed in a negative light (Seymour, 1992).

Tobias (1990) used case study methods in classroom studies of the experiences of nonscience majors enrolled in introductory physics and chemistry courses. The participant-observers recorded their perceptions in journals to provide a record of the research. The results, summarized by Hoots (1992), provide an insider's perspective.

...students describe course content as a continuum of unrelated facts lacking contextual meaning. They point to study exercises as efforts designed to facilitate mechanical responses rather than facilitate the processing of vitalistic interpretations; to feeling threatened by a sense of competitive isolation within overcrowded classrooms; and to finding themselves drowning in the swell and rush of voluminous details before they have the chance to grasp the fundamental design.... They feel hampered by their reluctance to invite help in translating the abstract symbols and language into meaningful, relevant constructions (pp. 300-301).

Navarra, Levin, and Navarra (1992) noted that college science teaching is typically organized around discrete topics dictated by the contents of a required textbook. Such courses are fact-oriented and the didactic tendency is to deliver content knowledge through the expository lecture. Students generally have little or no opportunity to engage the professor in meaningful dialogue about the concepts and principles presented. Large lecture classrooms demand silent attentive students who listen passively. Students understand that they will be rewarded by their silence and attentiveness when they respond to the battery of multiple choice questions on exams.

Elements of Reform

In a series of discipline-oriented workshops sponsored by the National Science Foundation (NSF), participants drawn from a wide spectrum of institutions in the research and education communities focused on the problems of American undergraduate science education (NSF, 1988). From the perspective of all the workshops, the NSF was urged to expand or initiate programs in a number of major educational areas including laboratory instruction, course and curriculum development, faculty and student concerns and the retention of under-represented students. The curriculum, in its broadest sense, was viewed as needing considerable attention. It was suggested that efforts should be encouraged to analyze and restructure courses and curricula. Two kinds of faculty-oriented efforts also were identified. Included were efforts intended to attract and motivate research faculty to work on improving teaching and those aimed at assisting teaching faculty to achieve and maintain technical competency.

As the NSF attempts to give institutionalized shape and direction to the reform of college science teaching, independent initiatives are underway. Science departments and faculty at a number of colleges and universities are involved in efforts to reinvigorate entry-level classes in physics, chemistry, biology, and other sciences -- frequently with grants and guidance from private foundations, scientific societies, and state and federal sources. Navarra, Levin, and Navarra (1992) referred to these diverse attempts at curriculum reform as the new paradigm of college science teaching. Some suggest that current reform efforts signal fundamental changes in notions of science teaching and learning as constructivist epistemologies replace traditional views of the teacher as knowledge transmitter and behavioral engineer. If so, science teachers would have to review their conception of teaching, to treat learning as an active process of constructing concepts rather than a passive process of absorbing information, and to understand that learning is sometimes enhanced in social interactions of students. For many who advocate the reform of science teaching practices, the notion of teaching for understanding may embody more than a theoretical perspective. It may define a new standard for practice. However, despite enthusiastic support for this conception of teaching traditional, didactic forms of pedagogy, dominated by lecture, textbook readings and memorization, persist in our science classrooms (Rigden and Tobias, 1991). Stofflett and Stoddart (1994) suggest that this results from the fact that reform efforts are not sufficiently focused on teacher learning. It may have been previously assumed that reform would follow if teachers were provided with innovative teaching materials and

instructions for their use (Shulman, 1986). However, a number of studies have suggested that teachers often fail to implement science curricula in ways designers intended. Smith and Anderson's (1984) work, for example, demonstrated that a marked difference resulted between the intended and implemented curriculum when teachers and curriculum developers held different views about the nature of student learning and scientific knowledge. This is not a surprising result. After years of learning science in didactic classrooms most teachers have no experienced-based teaching conceptions other than didactic pedagogy. Such views can be explained by the notion of a reciprocal relationship between subject matter and pedagogy, meaning that the way science content is learned by teachers also influences how pedagogy is learned.

Teachers' conceptions of teaching are viewed as the consequences of pre-service educational experiences, formal academic coursework, practical classroom applications and experiences outside of school environments. Current research has focused on various aspects of teacher conceptions, their formation (Shulman, 1986) and potential impact on instructional practice (Lederman, Gess-Newsome, and Latz, 1994). Work by Hashweh (1985), Hauslein, Good and Cummins, (1992), West and Pines (1985), and others, used card-sort tasks, semantic networks and concept maps to probe the structural aspects of teachers' conceptual content knowledge and its role in professional development. Conceptual pedagogical knowledge has been less intensely investigated. Notable exceptions include work by Leinhardt and Smith (1985) which studied the conceptual and procedural aspects of pedagogical knowledge.

Conceptual content knowledge refers to those aspects of subject matter knowledge which are accessible and readily retrievable from long-term memory. Conceptual pedagogical knowledge refers to the largely implicit forms of teacher knowledge that may be incorporated into the production systems that comprise procedural knowledge (Hoz, Tomer and Tamir, 1990). Teachers are not usually required to explicate this knowledge of which they are less aware than the explicit procedural knowledge (instructional skills). This aspect of pedagogical knowledge probably overlaps with what has been described as implicit theories in much the same way that understandings and beliefs overlap. Both are forms of knowledge, but when they differ understanding is meant to include knowledge which has an academic component. However, implicit theories are far from being the neat and complete reproductions of the educational psychology found in textbooks. Instead, they are more likely to represent eclectic aggregations of cause-effect propositions and generalizations drawn from personal experiences, including beliefs, values and biases (Clark, 1988). The distinctions drawn by these authors between different aspects of pedagogical knowledge appear to be based upon the degree to which the knowledge is accessible as a coherent learning theory, and its origins, whether in formal academic learning or in nonformal experiences in or outside the classroom. A more inclusive meaning of the term conception is suggested by Toulmin's (1972) notion of a conceptual ecology. Here the term is meant to include the learner's content knowledge, epistemological commitments, beliefs and knowledge outside the field – and more specifically, the meaning individuals have constructed from integrating

their content knowledge, beliefs and theories. This somewhat broader interpretation is applied to teacher conceptions in this inquiry.

Science educators have generally recommended the application of a constructivist perspective to teaching and curriculum developers may incorporate that perspective in curriculum design. As Barnes (1982) has indicated, an intended curriculum consists of both a set of classroom materials and a theoretical perspective. However, constructivist epistemology includes a wide range of learning theories. For example, Lawson, Abraham and Renner (1989) emphasize the role of hypothetico-deductive thought in the development of students' scientific knowledge while others emphasize the role of prior knowledge and conceptual conflict in science learning (Posner, Strike, Hewson and Gertzog, 1982). Social constructivism recognizes the importance of the interplay between language and actions in student learning in social settings (Vygotsky, 1978). These various theories are here subsumed under the theoretical framework of constructivist or cognitive learning theory which recognizes the role of subjective experience, or cognition, in knowledge development. From this perspective, learners as participants in the learning process, construct meaning by interpreting new information and connecting it to their prior knowledge. This perspective contrasts with learning theory which assumes that students passively learn or modify their behavior as a result of knowledge acquisition from external influences.

Some science educators have proposed that teacher education courses should be revised to include conceptual change learning experiences as a counter to didactic pedagogy (Stoddart, 1991; Stoddart and Stofflett, 1992).

The rationale is as follows: If the pedagogy through which teachers learned science content is in fact a determinant of how they understand and teach content, then teachers will need to restructure their content knowledge through conceptual change methods. The experience of learning content that way should facilitate teachers' understandings of both content and pedagogy. Such experienced-based learning is designed to provide a conception of desired practice based on theory (Duschl and Gitomer, 1991). However, this approach appears limited to the extent that it does not provide a way for teachers to understand how traditional and constructivist teachers think and act in actual classroom settings or to relate these understandings to their own practice. Conceptual change theory also offers no way to evaluate the relative effectiveness, except on theoretical grounds, of either pedagogy in classroom application, although this would seem to be an important way to encourage teachers to accept the results of educational research. Classroom based research designed to meet these objectives would seem potentially useful in providing teacher education with the means to make alternative pedagogical conceptions more explicit and plausible than might otherwise be possible through conceptual change instruction alone.

A Research Model for the Study of Science Teaching

Earlier studies of classroom teaching, set within the psychological research tradition, assumed that complex forms of situation-specific human performance could be understood in terms of underlying generic processes. In studying teaching, this approach sought to identify generic forms of teaching behaviors that correlated with student performance on statistical

tests. Such studies, in effect, "reduced the teacher to a characteristic and the student to a score on an achievement test" (Hashweh, 1985, p. 4).

Components of the teaching-learning environment such as subject matter, classroom contexts, psychological characteristics of students and other factors not easily assessed on standardized tests, were essentially ignored. However, contemporary views of science education reject the notion that effective teaching rests upon pedagogical skills that are independent of classroom contexts. A growing body of research presents convincing evidence to the contrary (Leinhardt, 1983; Leinhardt and Greeno, 1986).

Progress in the field of research on science teaching depends upon demonstrations of patterns that are observable and applicable across classrooms. Unlike process-product research methods, a better understanding of the relationship between teacher conceptions, practice and student learning requires studies that are supported by rich qualitative data from a small number of classrooms – a research agenda that rests upon interpretative methods applied in longitudinal studies. This is the approach employed in this inquiry which compared two divergent forms of college science teaching. The pilot study included descriptive accounts of traditional and constructivist-based teaching. The main study began with the selection of chemistry teachers, extended into their classrooms to observe their practices, and concluded with qualitative and quantitative assessments of student learning outcomes.

Chemistry Curriculum Reform at L.S.U.

In the fall semester of 1991, an experiment in chemical pedagogy appeared alongside various chemical experimentations underway in the

Louisiana State University (LSU) Department of Chemistry. As a topic for educational research, the course's potential was readily apparent to the author, for unlike arguments for reform, examples of innovative pedagogy are still relatively rare (McLaughlin and Talbert, 1993).

Chemistry 1202 is typically taught in a conventional, large-lecture format. Designed primarily for science majors, it is a course where diverse science and mathematics backgrounds and experiences are seen among the students who enroll. High drop-out rates are not uncommon in some sections (see Appendix M). Chemistry 1202 also includes a few declared chemistry majors and the course serves as an alternate route to the major. Dissatisfied with the earlier results of a conventionally taught version of the course, one faculty member, whom I refer to as Dr. Henry, developed and incorporated a number of innovative instructional and assessment strategies and revamped the format. The 1990 publication, They're not Dumb, They're Different – Stalking the Second Tier by Sheila Tobias was a significant influence on his decision to develop these innovations. Because of its decided emphasis on constructivist-based teaching, the term conceptual chemistry is applied when referring to Henry's course throughout this study.

The 1202 course syllabus includes a range of topics designed to combine a general review of chemistry with a rigorous foundation. Included are the general topics of Liquids and Solids, Chemical Equilibrium, the Ozone Hole, Acids and Bases, Entropy and Chemical Reactivity, Oxidation and Reduction, Electrochemistry, and the Chemistry of the Main Group Elements I and II.

The content domain of chemical equilibrium was selected to demonstrate topic-specific similarities and differences among the classes. Surveys reveal that equilibrium, oxidation-reduction, and reaction stoichiometry are rated among the most difficult chemical topics for students to learn. Of these, equilibrium is usually rated as the most difficult. However, chemical equilibrium is a major unifying concept in chemistry. An understanding of the topic is fundamental to understanding other topics such as oxidation-reduction and acid-base behavior. The topic also has served as a content domain for problem-solving research (Camacho and Good, 1989), studies of chemical misconceptions (Hackling and Garnett, 1985) and the structure of domain knowledge (Gussarsky and Gorodetsky, 1988; Maskill and Cachapuz, 1989, Wilson, 1994), and conceptual change (Gorodetsky and Hoz, 1985). These studies demonstrate the utility of the subject for a variety of research topics as well as providing information directly relevant to this inquiry.

LSU's Conceptual Chemistry course provided a unique research opportunity to obtain information that could facilitate understandings of constructivist alternatives to conventional teaching practice. As a dissertation research topic, classes based on a constructivist model are systematically compared to classes taught by using traditional, didactic methods. The new pedagogy advocated by reformers promises to enhance the kinds of cognitive and affective outcomes that the traditional system of science education has been ineffective in producing (McLaughlin and Talbert, 1993). However, few examples have convincingly demonstrated this in practice. By identifying conceptual chemistry with constructivist

teaching, I have assumed that it is consistent with this vision of educational practice which is held by many reformers. The comparative analysis used in this research is designed to provide information to affirm or refute claims that significant differences should exist in the theory, practice, and student outcomes of these courses. Study results also may serve to inform practitioners of some of the conditions that could enable or constrain the application of pedagogical innovations in college science classrooms.

I proposed in this study to compare two divergent forms of college chemistry teaching – a comparison that required the *a priori* selection of examples of each. My initial conception of traditional college teaching was based upon a composite description derived from case studies of secondary and college classrooms and from my own classroom observations (Table 1). However, I did not assume that all traditional classrooms would necessarily look and act alike although the literature had associated high course attrition and negative attitudes with more traditional forms of science teaching. Similarly, while innovative pedagogies all appear to depart substantially from conventional practice, I understood that they also may differ from one another in significant ways. My earliest impression of

Table 1
General characteristics of traditional and constructivist forms of teaching based on literature

	Traditional	Conceptual
Curriculum	Discrete topics dictated by text	(redesigned by teacher)
Instruction	Expository lecture (noninteractive)	Multiple strategies (interactive)
Assessment	Multiple choice exams	Multiple forms of assessment

Henry's course was formed in an initial meeting in which we reviewed the intended curriculum. These general impressions constituted the understandings and biases with which I began the study.

Framework for the Research

In this study, classroom teaching and learning are viewed as complex interaction among teachers and the contexts of subject matter and students. The research framework assumes that teaching can be understood through teacher conceptions, including teacher knowledge and beliefs. Classroom practices in an enacted curriculum are understood as a consequence of teacher conceptions. That is, teaching is understood as an action that is partly determined by teachers' intentions, knowledge and beliefs, (Clark and Peterson, 1986; Shulman, 1986). Teaching is also partly determined by a number of external influences such as the nature of subject matter, students or other contextual factors (Hashweh, 1985). However, as indicated by Cronin-Jones (1991) and others, a teacher's teaching objectives are not necessarily the same objectives as determined by curriculum designers or a science department. It is assumed that such externally imposed objectives can be transformed in a manner that is mediated by a teacher's own content and pedagogical knowledge, theories and beliefs. If so, these two domains constitute a primary influence on teaching as it is actually practiced in a classroom. In Shulman's (1987) model of teachers' pedagogical thought, it is also assumed that some part of a teacher's content and pedagogical knowledge may be integrated into a single knowledge base. For purposes of this study, it is presumed that at least some degree of interaction exists between them.

The primary focus of this inquiry is teachers' conceptions of teaching, which for purposes of the research includes their personal understandings or conceptions of learning and subject matter and how these are linked to strategies for organizing, representing and testing course content. Cognitive and affective outcomes comprising student learning are seen to result from the dynamics of teaching and student prior knowledge and attitudes. This model served as a research framework for comparing teachers' conceptions and classroom practice, and the evaluation of student learning outcomes in traditional and conceptual chemistry courses. Figure 1 is a Vee diagram of the research (Gowin, 1981).

Research Questions

The research questions addressed by this study include:

- 1) What conceptions of teaching are held by teachers in traditional and conceptual chemistry?
- 2) How do these conceptions influence classroom teaching practices?
- 3) What differences result in student learning outcomes?

Definitions

The following definitions are applied for purposes of the study:

- 1) Conception of teaching - in this study the term denotes a pedagogy based upon the teacher's personal understandings and assumptions about subject matter and student learning. It follows from Toulmin's (1972) notion of a conceptual ecology which is inclusive of the learner's epistemological commitments, theories and knowledge.

- 2) Formal/nonformal science - formal methods include special symbolic representations such as mathematical symbols and the explicit rules and procedures for working with them. Nonformal methods include qualitative representations and temporary models opportunistically devised to aid thinking about scientific phenomena.

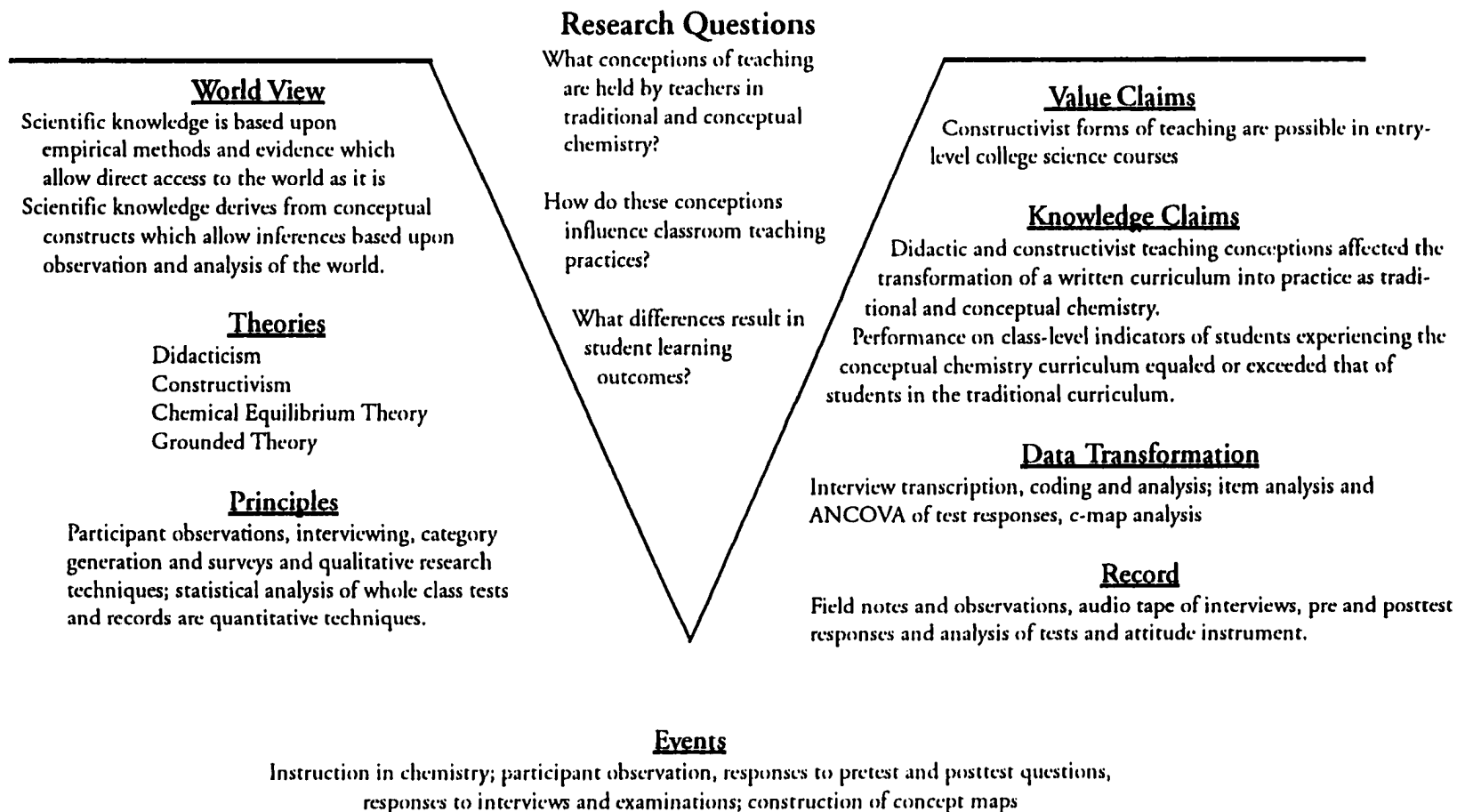


Figure 1
Gowin's vee of research

CHAPTER 2

LITERATURE REVIEW: THEORETICAL BASE

Research on Teaching

Historically, research on teachers and teaching practices derives from two different intellectual traditions. The origins of the process-product tradition can be traced to the style and theory of behaviorist psychology which viewed teacher research as research in which at least one variable consisted of a behavior or characteristic of teachers. Process-product researchers focused on the criteria of teacher effectiveness which largely lay outside of the immediate classroom. For example, achievement was measured by end-of-year standardized achievement tests or end-of-unit norm referenced performance tests. Research in this tradition emphasized the use of quantitative methods which highlighted the role of student achievement outcomes, but essentially decontextualized the analysis by reducing the teacher to a characteristic and the student to a score on an achievement test (Hashweh, 1985).

By contrast, the interpretive research tradition, including classroom ethnographies and sociolinguistic studies, views classrooms as socially organized environments. Emphasis is placed on qualitative methods to describe the influence of contextual factors embedded in the classroom and larger contexts in which the classroom is placed -- the school, community, or society. In this tradition, teaching is defined more by the reflexive participation of teacher and students than specific teacher behaviors.

Shulman (1986) observed that the substantive differences between the two traditions lie not so much in their research methods, but in their

conceptions of teaching. Both traditions, however, are alike in that they ignored the substance of classroom life, the specific curriculum content and subject matter being taught.

Contemporary research in teaching is heavily influenced by the findings of cognitive psychology which have brought into question the adequacy of earlier behaviorist explanations of complex human thinking and performance. Studies of teacher cognition seek to understand teachers' actions in terms of their thought processes. Beginning with the premise that a connection exists between what teachers think and what they do, Clark and Peterson (1986) proposed a model which links in a reciprocal relationship, teacher thought and teacher action. Teacher thought includes theories and beliefs, planning and decisions, while teacher action and its observable effects include teachers' classroom behavior and students' classroom behavior and achievement. Shulman (1986) considered Clark and Peterson's review and indicated that there was clearly a need to relate research on subject matter understanding to cognitive studies of teachers and the instruction they provide. The perspective held by these authors is that teaching practices are guided by the conception of teaching held by a teacher.

Some evidence to support these assumptions is provided by Hewson and Hewson's (1987) review of the interpretation and use of science curriculum materials and study guides by teachers. Although the conceptual change model of teaching was implicit in these materials, the authors observed that teachers were consistent in using one of two distinct approaches which were identified as didactic knowledge acquisition and

discovery knowledge development. Similar observations were obtained in other studies of teacher conceptions of teaching (Morine-Dershimer, 1989) and in Marek, Eubanks, and Gallaher's (1990) study of the use of the learning cycle.

Conceptions of Learning

Hewson and Hewson (1987) concludes that teachers employing different teaching approaches may hold different conceptions of student learning. Work by Hollingsworth (1980), Hashweh (1985), Cronin-Jones (1991), and Stofflett (1994) also suggests that epistemological assumptions about science learning may be involved in virtually every teaching episode.

Such assumptions can be thought of as theoretical frameworks that offer explanations to teachers for the way students acquire new knowledge and skills and the ways existing knowledge and skills are modified. A prevailing theory, deriving from behaviorist foundations, assumes that students learn, or modify their behavior, as a passive response to various external phenomena. Learning is understood to be an essentially linear and sequential process where complex understandings result from a step-by-step accumulation or accretion of knowledge. As the basis for a teaching model, it focuses on the transmission of knowledge and changing the environment to reinforce associations between responses when learning does not occur as desired (e.g., reinforcing learning by reteaching topics). Behaviorist influences on assessment practices are also evident in the criterion-referenced testing model in which testing is closely tied to instruction. The model assumes that all important learning objectives can be specified and measured completely by standard tests.

Cognitive theory assumes that learning is an internal construction of knowledge as opposed to the external instruction of knowledge purported by didactic teaching conceptions (Marek, Eubanks, and Gallaher, 1990). Learning is seen as an active, constructive, and goal-oriented process dependent upon mental activities of the learner. It is concerned more with the acquisition of knowledge and knowledge structures rather than behavior *per se*. Knowledge is that which is learned. Behavior is understood as the result of knowledge, not knowledge itself. Considerable emphasis is also placed on the role played by prior knowledge in learning. Consequently, learning is viewed as a process in which students take in information, interpret it, connect it to what they already know, and reorganize their mental structures to accommodate new understandings (Shepard, 1991). Some cognitive psychologists go so far as to suggest that analogical reasoning which involves prior knowledge forms the basis of most cognitive learning (Rummelhardt and Norman, 1981). The end result, however, is the construction of personal meaning. This does not assume that learners construct meaning in isolation. Learning may also involve social interaction and cultural transmission (Vygotsky, 1978).

Cognitive theory also purports that learning is best represented by complex knowledge structures rather than simple associations. Cognitive-based assessment employs various methods to deal with the complexity of cognitive function and is focused on analyzing performance in terms of thought processes, i.e., indications of inductive and deductive reasoning.

Cognitive theory, which underlies constructivist forms of pedagogy, requires that teachers move beyond fact-based ideas of knowledge and

actively involve students in the learning process. The pedagogical assumptions of constructivist epistemology also require that such interrelated issues as preconceptions, concept acquisition and cognitive restructuring are addressed. For example, inquiry teaching holds a cognitive view of learning in which students confront preconceptions and construct scientifically appropriate concepts through the integration of science processes (i.e., observations, data-gathering, model building, and prediction).

Different teaching and testing procedures may not be exclusive in terms of learning objectives. For example, didactic and conceptual change teaching stress the need to present the desired scientific conception, although teaching practices may differ substantially. While didactic forms of teaching tend to dismiss student responses not in agreement with concepts being taught, inquiry and conceptual change teaching propose that student conceptions are important, even when inappropriate, and suggest that students be encouraged to explore the advantages and limitations of their concepts.

Constructivist theoretical perspectives represent the mainstream of thinking in both psychology and education. Despite this, didactic pedagogy persists in the nation's science classrooms (Tobias, 1990; Marek *et al.*, 1990).

Science Knowledge and Science Teaching

Science exists in several forms. For example, it exists as public knowledge organized in the corpus of published texts and literature. This form of knowledge represents the common understandings of experts in a scientific discipline and it constitutes a large part of the science subject matter taught in the classroom. Science also exists as private understandings

and procedural knowledge or skills in the minds of scientists and students of science. Cognitive psychologists and science educators have focused much of their research efforts on this private dimension of scientific knowledge in science domains. One of the important ways science knowledge is conceptualized in such studies is in the form of semantic networks of interconnected concepts and propositions.

Science content knowledge supports lesson structure and it serves as a resource in organizing topics, selecting examples and in formulating teacher explanations. Science content knowledge is composed of theories which reside in conceptual systems. A finite set of embedded or scientifically accepted theories exist in each scientific domain. Each theory in turn, consists of a set of propositions or postulates necessary to define the theory. Such propositions, the facts of science, form an integral part of teacher classroom explanations of science topics, as they are organized and represented in both declarative and procedural forms.

Science teachers transform their understandings and performance skills into pedagogical representations and activities, which reflect their understandings of content as well as their beliefs and understandings of students' knowledge and learning characteristics. Thus, teacher representations of subject matter confer a social dimension to cognition by transforming the contents of teacher thought into public form. There are two considerations which derive from this observation and which relate to the study's research questions. First, the pedagogical significance of content representations may lie in the notion that the selective emphasis of some forms over others may privilege some students and handicap others. Second,

content representations may be conditioned by teachers' epistemological assumptions about subject matter and student learning. When such understandings are held in common among teachers within a science discipline, they may represent what some researchers have referred to as a tradition or culture within a discipline.

Content Organization and Representation in the Physical Sciences

There seems to exist a firmly established logical structure of subject matter which exerts a powerful limiting influence on the ways in which the content of science courses is organized and represented. It should be remembered, however, that the logical structure of subject matter in a discipline, or as presented in a scientific paper or a textbook, is not something fixed and unchanging; rather it is the result of a reorganization of raw knowledge as it arises within the context of discovery – a translation of private understandings into public science on the basis of criteria which are far from self evident and which are not always made fully explicit. The purpose of this reconstruction is to obtain a more adequate representation of science as defined by underlying epistemological assumptions about science and scientific knowledge.

The central goal of science is to achieve prediction and explanation by devising special theoretical knowledge which parsimoniously (i.e., on the basis of a minimum number of premises) permits inferences about the largest number of observable phenomena (Reif and Larkin, 1991). This goal imposes stringent requirements for generality to ensure that a very small number of theoretical premises can lead to prediction about a great number of phenomena. Consistency is necessary to guarantee that different

arguments do not lead to contradictory predictions and precision so that unambiguous predictions can be made to any desired degree of precision. To achieve these requirements of scientific knowledge, scientists have invented formal methods deliberately designed to implement long inference chains with great precision. Such methods attempt to augment human cognitive capabilities by devising special symbolic representations and explicit rules for working with these. Examples include many kinds of mathematical formulations such as algebra, calculus, vector analysis, etc. The use of formal knowledge requires the ability to interpret abstract mathematical symbols appropriately.

This aspect of scientific knowledge has been described as the mathematization of phenomena, a process of attributing mathematical order to the natural world. Scientific formalism requires various representations of knowledge that are in part image-based and in part based on numbers arranged in tables, equations and mathematical models (Roth and Bowen, 1994). These socially accepted forms of representation are used to transform implicit understandings into explicit, public knowledge. Roth and Bowen (1994) noted that this experience promotes an objectivist epistemology that assumes that the universe has a fundamental structure that is isomorphic with mathematical symbolism. The relationship implies that we have access to nature as it really is and it underlies the notion that scientific knowledge, particularly its mathematical forms, represent truth; that is, the case for its importance and validity is prima facie. Thus, teachers may come to rely heavily on the formal methods, believing these are the essence of science. Science and students' knowledge may then be largely

viewed in terms of the capacity to decode mathematical symbolism and not as a conceptual structure enabling prediction and understanding through inferential thought. Larkin (1983) observed that traditional teaching practices in the physical sciences place an undue emphasis on precise mathematical formulations. DiSessa (1987) goes so far as to suggest that this emphasis on quantitative explanations may throw a veil of numbers over conceptual understanding. These and other authors speculate that many students may come to believe that the use of seemingly vague verbal or pictorial descriptions are inappropriate in scientific contexts.

However, there is ample evidence that scientific knowledge also derives from nonformal methods that exploit human perceptual processes and qualitative reasoning capabilities. Such methods can be devised to be consistent with more formal methods (i.e., mathematical formulations). However, science courses rarely succeed in teaching students their complementary use (Reif and Larkin, 1991). Examples of nonformal methods include use of verbal and visual representations. Visual representations may be diagrams or pictures that explicitly indicate or correspond closely to direct sensory perceptions of the physical world, or they may represent highly abstract concepts far removed from the observations which they are designed to describe. In addition, simple mental models are often used in conjunction with such representations to reason qualitatively about complex processes.

For example, Camacho and Good (1989), Larkin (1981), and others have established that a substantial amount of qualitative reasoning is involved in successful problem solving by experts. Similarly, Heller and Reif

(1984) and Reif (1987) observed that physicists typically employ multiple representations when working standard textbook problems, including qualitative sketches that guide their selection of mathematical equations. The analysis of expert problem solving underscores two aspects that appear relevant to teaching. The first is that problem solving procedures used by physicists typically proceed by successive refinements starting from gross global descriptions to successively more detailed descriptions. Such procedures seem to involve planning at various levels. They also exploit the utility of different symbolic representations to describe the same problem at different levels. These may include verbal or pictorial representations for global descriptions and mathematical symbolism for more specific descriptions. Chemists also use microscopic, symbolic, and macroscopic representations when solving chemistry problems. While most activity may take place in the symbolic framework, connections are maintained between the other types of representations. However, like physicists, chemists typically tend to condense these frameworks by simply quantifying the concepts and representing problems quantitatively when teaching.

Science Learning

Cognitive Measures

Evaluations of student concept learning and problem solving tend to be group oriented and generally employ cognitive measures such as achievement tests. Such tests are based on average performance and aim to assess the group's achievement score relative either to former achievement scores or to a standardized group achievement (norm). However, contemporary research on science teaching and learning has focused less on

such global measures and more on individual learning. In the cognitive learning tradition, assessment is grounded in fundamental epistemological assumptions that knowledge is an individual construction of concepts and concept relationships represented as a hierarchical network in long-term memory. It also acknowledges that many difficulties that students have in concept acquisition and problem solving may originate in the knowledge acquired prior to formal instruction and in the lack of awareness of that knowledge by of the teacher. This view is supported by empirical studies of different scientific domains indicating that students hold conceptions about the natural world that are often inconsistent with concepts and principles taught in science classrooms. Even after successfully completing science courses, many students persist in their preconceptions or hold ideas in one domain that contradict those in another. However, despite their limited predictive and explanatory power such conceptions may be useful in everyday life. This aspect of learning has been extensively investigated in recent years (Driver, 1989; Driver, Guesne and Tiberghien, 1985, Renner *et al.*, 1990).

The recognition that science learning may sometimes require changing students' conceptions rather than simply adding new knowledge to existing knowledge constitutes a significant insight for science education and has contributed to the development of cognitive conceptions of teaching. However, previous studies suggest that many teachers do not address misconceptions even when they may be indicated by student errors on exams. Hashweh's findings (1985) support the idea that teachers' conceptions of teaching and learning influence the significance attached to misconceptions in both instruction and assessment.

As suggested earlier, conventional tests of problem solving may reveal that a question is answered correctly or incorrectly, but often fails to examine what conceptions were employed. Consequently, students may pass courses with acceptable grades, yet retain their prior conceptions. However, limited though they may be, conventional, multiple choice exams are widely accepted as measures of the success of student learning and they are employed as such in this study. Summary scores and item analyses from course final exams are used as one comparison of class-level student outcomes. However, these measures are complemented by research-based instruments designed to capture aspects of individual learning that assess more directly the conceptual understandings students hold about chemistry and their applications in problem solving.

Affective Measures

Shulman and Tamir (1973) have argued that the affective outcomes of science instruction are at least as important as their cognitive counterparts. Affective outcomes may well determine what additional outcomes, cognitive or otherwise, are possible. If there is merit in such reasoning, it follows that studying the factors affecting student learning in science are incomplete without consideration of the affective domain.

Science educators have focused on student attitudes toward science largely because of assumed relationships between attitudes and a variety of factors. Studies reporting relationships, both strong and weak, between attitude and achievement, intelligence, gender, grade level, socioeconomic status and other variables are found in the science education literature. While these efforts have generated a wealth of literature, some sources

maintain that they have contributed only minimally to our understandings. One problem is that the attitude concept has been loosely defined and confused with other psychological concepts such as beliefs and values. However, most researchers now distinguish attitude by its evaluative component, the tendency to be for or against an object, event, issue or person (Fishbein and Ajzin, 1975). Schibeci (1984) reviewed some 200 studies conducted between 1976 and 1983 and concluded that:

1) Gender appears to be an important variable, both alone and in interaction with other variables.

2) The effect of specific science programs on attitudes varies considerably. There appears to be no consistent set of results for this variable.

3) Home background and peer group variables are probably important, but the influences are not direct.

4) Science should be divided into physical and biological sciences. Students' attitudes toward the biological sciences appears generally to be more favorable than to the physical sciences.

5) Favorable attitudes toward science appear to decline as students move to progressively higher grades.

Attitude theorists offer three reasons for attitude research. First, attitudes are relatively enduring; that is, people's feelings toward objects and issues are relatively stable over time. Although attitudes can change, such occurrences are not random; something happens to cause the change. Second, research suggests that attitudes are learned and likely form fundamental components of students' conceptual systems. Third, attitudes are related to behavior; actions often reflect feelings toward objects and issues.

Recent advancements in attitude assessment and observed behavior have served to improve consistency to the point where most experts agree that attitudes and behavior are related in a probabilistic manner. Obviously, consistency between attitude score and subsequent behavior is of paramount importance, if attitude inventories are to be used to predict behavior.

As noted by Tobias (1990) and others, regardless of one's position on the reliability and validity of science achievement scores, these are the measures traditionally used to determine who the good science students are. Consequently, these measures may be most influential in the students' attitudes toward and desire to pursue science. The links between attitude and achievement are likely determined by the day-to-day, week-to-week achievement that a student has in the science classroom.

CHAPTER 3

METHODS

My perspective on Henry's conceptual chemistry course was that it afforded an opportunity to observe and document an innovative alternative to traditional practices. This suggested that the research should proceed ex post facto, considering the course to be an experiment in progress. Consequently, the initial research focus was on developing a rich, descriptive account of the implementation of a model of chemistry pedagogy, and students' encounters with that model, within the social dynamics of a college classroom. This research objective required that no attempts would be made to influence either course content or instructional strategies. Research methods were required that were essentially non-interventionist or non-experimental in nature. Interpretive research methods, dependent upon a detailed descriptive foundation, were incorporated into the study to meet this objective. These methods also required that the study be conducted within the subject's natural setting, i.e., the classroom.

A second course, taught by a Dr. Reed, was selected as a conventionally taught alternative to Henry's course. The subsequent inclusion of Reed's traditional course located a naturally occurring point of contrast to the conceptual course, in effect varying teaching techniques, and allowing for a comparative analysis of two natural experiments in chemistry pedagogy.

My selection of Reed's class was certainly not accidental. Prior to the beginning of the fall semester, I had access to class enrollment records from previous semesters. Tobias (1990) and others claim one of the defining

characteristics of traditional science pedagogy is its relatively high student attrition rate. I had reasoned that a simple calculation of percent drop-outs from previous semesters could serve as at least one criterion for identifying classrooms taught in conventional formats. Other criteria such as the contents of the intended curriculum could also be used. Preliminary classroom observations would help confirm or negate my selection.

As the study evolved, questions concerning teacher versus method effects in the conceptual course suggested that a replication of the study would help determine the extent to which the course methods were transferable. It was during this time that another member of the faculty, Dr. Collins, decided to adopt Henry's revised curriculum. Collins would be teaching the course during the next semester (Spring, 1993), and she readily agreed to participate in the study. For comparative purposes, at the end of the semester a second course was selected from several sections of chemistry 1202 that would be taught during the upcoming semesters. Selection was again based on student attrition records and the proposed curriculum. This course, designated as traditional, would be taught by Dr. Hoffman. With the inclusion of the two sections taught by Collins and Hoffman, the investigation became a longitudinal, multicase study.

Research Design-Overview

The study was conducted in two phases. The pilot phase, which began in the fall semester of 1992, utilized qualitative research methods (Bogdan and Biklen, 1982; Rist, 1982; Patton, 1989; Seidman, 1991; Gallagher, 1991) to compare teaching and learning in conceptual and traditional chemistry classrooms. Data collection and analytical methods employed

classroom observation, unstructured interviews, document analysis, and constant comparison of emerging themes and categories.

The data collection methods and analytical procedures applied in the second phase of the study were initially tested and refined during the pilot phase. The second phase, which spanned the time period from the Spring Semester of 1993 through the Fall Semester 1994, involved four different classrooms and incorporated research-based instruments to compare student cognitive and affective outcomes (see Appendix A). Data collection methods included classroom observations, structured interviews, the use of course and Department records, and surveys. After the data were collected, triangulation provided for application of qualitative and quantitative analytical methods (Jick, 1979).

Limitations

One of the important limitations of the study relates to its research design, which did not allow a disaggregation of the multiple instructional and assessment components of the conceptual chemistry courses. These components were treated in the aggregate, so direct comparisons could be made with the traditional courses. Further work will be required to disentangle the relative effects of demonstrations, visuals or cooperative groupings on learning outcomes. In this study, these components are considered in combination.

The Setting

The study was conducted within the physical environments of Choppin Hall and Peabody Hall. Choppin Hall houses both the Chemistry Department and the Biochemistry Department, and Peabody Hall

houses the College of Education on the LSU campus in Baton Rouge, Louisiana.

All classroom observations were conducted in a large lecture auditorium located on the first floor of Williams Hall, a four-story building immediately adjacent to Choppin Hall. Room 103 of Williams Hall is equipped with a laboratory table situated on a raised platform located in the front of the room, two screens for overhead projectors and large blackboard. With a seating capacity of 300, this facility is utilized for the introductory chemistry course sequence 1201 and 1202, as well as for seminars conducted by the Departments of Chemistry and Biochemistry.

Because I assumed that the choice of interview settings could affect respondent reactions, interviews were conducted in a uniform location to equalize possible setting effects across respondents. All student interviews were conducted in Room 212 of Peabody Hall. Teacher interviews were confined to the teachers' offices located in Choppin Hall. Student interviews, which included concept mapping and problem solving, were of necessity more structured, while teacher interviews were less so. The typical interviews for students lasted from approximately 45 minutes to one hour. Teacher interviews were usually completed within 30 minutes.

Rationale for Research Methods

Participant observation is not a single method or technique. It may be best described as an omnibus field strategy, simultaneously combining observation, direct participation, analysis and interviews. The extent of researcher participation is, in effect, a continuum which ranges from complete immersion in the environment to complete separation as a

spectator. The research value of such combined approaches is based upon the premise that the inherent limitations in any single method can be compensated by employing multiple and independent methods, a type of between-method triangulation that tests the validity of the research findings (Jick, 1979).

Though most of the fall semester of 1992, I would remain essentially a spectator in both classes, simply noting what was taking place, who the actors were, and trying to focus through the multiple layers of context that combine to influence the curriculum implementation process. Earlier conversations with my major professor had convinced me that some of the answers to what and how contextual factors influence conceptual and traditional teaching could be pursued using case study approaches. Qualitative, field-based research could illuminate the everyday meanings of context important to the teachers and students. In practical terms, this could be important to demonstrate to a school or science department that innovative pedagogy can (or cannot) work here. This general and highly pragmatic goal required that I explore, for example, some of the contextual factors that the participant teachers recognized as most crucial to their individual practice and beliefs. Science faculty conceptions of science knowledge and pedagogy might be linked to a subject matter culture, or the criteria of educational success supported by a department's admission standards or its pedagogical norms and student assessment practices. The study also sought to describe how teacher conceptions linked subject matter and pedagogy in practice and how this might influence student learning outcomes. This information, in turn, could be useful in

demonstrating how classroom teaching practices might be transformed. This should not, however, be interpreted as a prescriptive approach. Its utility would lie primarily as an example of how teaching can be adapted to accommodate different contexts and objectives.

Entry into the Field

Entry into the classrooms required that I negotiate with gatekeepers to gain access. Henry had been immediately agreeable to my suggestion that his course might serve as the subject of a dissertation study. Reed approved less enthusiastically, although he was no less agreeable. His only stipulation on my participation in his classes was that I not be intrusive.

Participants

During the second phase of the study, which spanned four regular semesters, research was conducted in four different sections of Chemistry 1202. A total of four Chemistry faculty and eight students were involved in observations or in-depth interviews. Henry and Collins taught the conceptual courses, Reed and Hoffman were the instructors in the traditional classes. The student participants in conceptual chemistry included David, Derek, Grace and Frank. Michelle, Gary, Scott and Richard were enrolled in the traditional classes. By the end of the study, data had also been collected from 1,002 students who participated in Department final examinations, 312 students who participated in the attitude survey and 52 students (from two sections only) who took both the pre-and post-chemistry tests.

The Chemistry Students

The students included in the study were all enrolled in Chemistry 1202, the second course in the introductory sequence for non-majors.

During the second phase, these included Section 1 (Spring 1993) and Section 3 (Fall 1993), Section 6 (Spring 1994), and Section 2 (Fall, 1994). I assumed ability level and prior course work and experience of each class to be heterogeneous. All students enrolled in Chemistry 1202 were required to have taken, at minimum, the 1201 freshman chemistry prerequisite. The students were self-assigned to their classes. Student-level demographics were obtained from class rosters which were supplemented by survey information gathered from the students. This information included gender, class status, and declared major. Class-level data, including enrollment figures for all sections and final examination class averages and item analyses, were provided by the faculty or Department records.

Student interview participants were selected from a pool of volunteers from each section. My initial approach to selecting student participants was to purposefully sample the classes to ensure representation of the broadest range of student characteristics possible. This took into consideration such factors as gender, major (science or nonscience), and class level. At the beginning of each semester after the pilot phase, I spoke to the classes, describing the study and asking for volunteers for interviews. This typically provided a pool of 10-15 names of volunteers from which, after consulting with the professor, I could select a number for interviewing. The eight students represented in the study are those that were willing and able to participate in all phases of the interviewing process. Included among the student participants are a pre-med student, several engineering majors, a zoology major, a pre-nursing student, and a psychology major (Table 2).

Table 2
Student interview participants

Semester	Teacher	Students	Major
Spring, 1993	Collins	Grace	nursing
		Fred	psychology
Fall, 1993	Reed	Michelle	pre-med
		Gary	mechanical engineering
Spring, 1994	Hoffman	Scott	zoology
		Richard	chemical engineering
Fall, 1994	Henry	David	chemical engineering
		Derek	anthropology

The Chemistry Faculty

Henry designed and taught the first conceptual chemistry course to be offered in the chemistry department. Henry is an experimental chemist whose post-doctoral research was conducted at a European University in organometallic cluster chemistry. His classes were part of both phases of the study. Henry has published widely in professional journals, is the recipient of several significant research grants, and a number of awards for excellence in science education. His research orientation is toward chemical synthesis, involving descriptive and qualitative aspects. He attributes his motivation to redesign Chemistry 1202 to a general interest in improving Chemistry education and to reading the Tobias Report. He has taught chemistry at the university level for approximately 15 years.

Reed is a theoretical chemist whose background training includes a doctorate from an ivy league university in Chemical and Mathematical Physics. His training and extensive research experience indicate a strong quantitative orientation to chemistry research and education. In recent

years, Reed has devoted increasing amounts of time and effort toward science education. He was also a participant during both phases of the study.

Hoffman received his undergraduate and graduate degrees from European universities. He is a physical experimentalist with a strong quantitative background and considerable publishing experience with over 100 professional publications. He was formerly with the faculty of Mathematics and Physical Sciences of a European University and has maintained his association with several European and American professional and honorary societies, boards and commissions. Hoffman has taught at the university level for approximately 14 years.

Collins is a new faculty member who holds a doctorate in physical chemistry and biochemistry. She is an experimental chemist with publications in a number of professional journals. Her strong interest in chemistry education stems in a large part from her previous experience as a teacher in secondary chemistry and physics. Collins adopted Henry's course revisions to her own classes. Her teaching experience at the secondary and college level span some 15 years.

Data Collection Methods

Classroom Observations

During this study, data were collected over a two year period of classroom observations, interviews, and record analyses. Teacher classroom presentations were recorded on audio tape and selected sections of the tape record were transcribed verbatim. These transcripts formed the most significant portions of the data collected during the pilot and subsequent

portions of the study. Field notes, largely a record of what was observed in the classroom, were an important supplement to the tapes. I used them as a basic record of classroom activities, what the professors were doing during his/her presentations, i.e., using overheads, working problems on the blackboard, as well as an account of student activities during the class. The use of different data collection methods in descriptive studies attempts to enhance the fit between what is observed and recorded and what actually occurs.

Documents collected from each class included the syllabus, class rosters, handouts, homework, tests, and final examinations. A set of class notes provided in the conceptual classes later proved to be an important complement to the field notes. Upon request, the Department of Chemistry provided class-level statistics for each section of Chemistry 1202 including final examination scores and class enrollment figures.

After the pilot phase, as the study focus shifted from broad classroom observations to selected topics, teacher and student interviews became an increasingly important source of data. Demographic information relating to the participants' backgrounds and education were obtained during these sessions. Table 3 provides a summary of data collection methods employed throughout the study.

Interviews

Most investigators agree that ultimately the conduct of interviews depends upon effective probes. Seidman (1991) and others advocate probes for elaboration and explanation, clarification and completion of details. Most importantly, these authors recommend that structural interviews should not be conducted until

sufficient trials have suggested the placement and wording of probes required to adjust the variation that respondents offer in their answers.

Table 3
Methods of data collection with participants/topics

Participants	Method	Topics
Teachers	Classroom Observations Interviews	All chemistry topics selected: Chemical Equilibrium Academic background/teaching experiences, Course overview objectives, syllabus, materials, student assessment Conceptions of teaching/learning Content topic: Chemical Equilibrium
Students (Individual)	Interviews	Academic background/major educational objectives; attitude assessment Content topic: Chemical Equilibrium Concept map (Post-instruction) Interview about instances, Attitude assessment
Students (classes)	Exams Tests Records	Final examination scores and item analysis attitude test scores and item analysis Chemistry test -- qualitative vs quantitative; enrollment data

Following these suggestions, I conducted a number of interviews during the pilot phase. Based upon these pilot interviews, I was able to collapse several questions and cues into fewer words and establish general formats which were utilized during the rest of the study.

Teacher Interviews

All four teachers were interviewed at the beginning of the semester and once during the semester as their schedules allowed. The first

interview allowed me to preview the course in terms of general objectives, department requirements, use of text, test schedules, and size and characteristics of the class. The second interview was typically more structured and focused on the teachers' conception of teaching and learning and strategies for teaching specific topics, including Chemical Equilibrium. For the second interviews, I used a list of questions as probes. Some of the questions were stated indirectly as I did not expect the teachers to have their conceptions accessible to state in propositional form.

Student Interviews

Following White and Gunstone's (1992) recommendations, student interviews employed different methods as probes to evaluate student understandings of chemical equilibrium.

Concept Maps

Concept maps are a schematic device representing a set of concepts embedded in a framework of propositions. Instruction theoretically affects both the content and structure of student knowledge and such changes are reflected in concept mapping. (Ausubel, Novak and Hanesian, 1978). Mapping tasks usually require that students identify concepts, arrange them from general to specific and relate them in a meaningful way. During the structured interviews, students were asked to prepare a concept map to represent their understanding of the topic of chemical equilibrium. Maps were constructed using variations of the technique described by Wandersee and Abrams (1994) which allowed the student and researcher to participate in the co-construction of a map. Students wrote their responses to concept-electing questions on a blackboard and were

recorded by the researcher on index cards. The students were then asked to place the cards in an arrangement that made sense to them. The final arrangement constituted a concept map that could be verbally verified by the student. Students were then questioned in depth about their understanding of each concept to generate a set of propositions.

Interview-About-Instances

During the second interviews, the students were presented with a qualitative and quantitative representation of an equilibrium reaction and several possible outcomes. The students were then asked to solve the problems and explain the reasons for their decisions.

Research Instruments

Chemistry Test

As indicated earlier, traditional chemistry teaching at both secondary and college levels often fails to incorporate qualitative understandings as a pedagogical objection. Nurrenbern and Pickering (1987) employed both quantitative and qualitative representations of chemistry problems to evaluate students' knowledge in an entry-level course. The authors reported that while the majority of students could solve mathematical versions of the problems presented, they were unable to solve the qualitative or conceptual versions. These results clearly call into question the basic assumptions about what counts for learning in traditional teaching and testing. Quantitative problem solving as emphasized frequently in standard multiple choice tests may not represent the application of understood, conceptual knowledge as it has long been assumed. The test used in this study follows Nurrenbern and Pickering's

ideas for a chemistry pre- and posttest. Paired qualitative and quantitative questions, each worth 10 points, are presented in three topic areas to test group-level effects of traditional and conceptual teaching. Included are concepts on the topic of chemical equilibrium (questions 1 and 2).

Nurrenbern and Pickering's (1987), questions on reaction stoichiometry (3 and 4), and oxidation-reduction/electrochemistry (Appendix F). The test was administered pre- and post instruction of these topics to conceptual and traditional classes during the second phase of the study. Class average pre-and posttest scores for the whole test and the conceptual and quantitative sections were calculated.

Attitude Questionnaire

Measuring a student's attitude is basically an attempt to locate the student's position on an affective continuum. From this perspective, an attitude is the extent of liking or disliking an object or idea.

Unfortunately, this fairly simple distinction is not always apparent in the attitude research literature. For example, attitude studies include both research of scientific attitudes which are predominantly cognitive and attitudes toward science which are predominately affective.

An attitude questionnaire was administered to each class at the end of the semester. The instrument included 20 questions using a Likert scale containing five response categories ranging from strongly agree to strongly disagree. Six items were worded in a negative direction and 14 were worded in a positive direction. For purposes of this study, attitudes were defined in relation to a chemistry course, not chemistry or science in general. This also offered the psychometric advantage of simplifying the

instrument by limiting the items to a single rather than a multidimensional scale. The maximum score that could be obtained was 100 points and 20 points was the lowest score possible. A score of 60 indicated that a student was undecided on every question (Appendix G).

The attitude instrument was research-based in the sense that it derived from the context of the study. Field notes taken during the pilot phase included informal comments by students reflecting both positive and negative attitudes. For example, students were concerned with such issues as an overemphasis on problem solving, the fairness of tests, the sheer volume of material to be covered, or difficulties in knowing what content was important to learn and what wasn't. The students' comments, which reflected a diversity of student opinions toward various aspects of the course, were supplemented by my own impressions and observations to generate a pool of items which served as the basis for developing the attitude scale and questions. During the second phase, individual interviews of student participants, consisting of open-ended questions, were employed to compliment the quantitative measurements of class attitudes. The advantage of these interviews were that they afforded the students an opportunity to state their feelings and beliefs about the course and to elaborate on some of the reasons for their views.

Data Analysis

Qualitative Analysis

The main aspects of this study which dealt with teacher conceptions, were based upon grounded theory. A grounded theory is one whose component ideas are grounded in the data collected (Hutchinson, 1990).

The first purpose of the study was to identify and describe the categories of teacher conceptions influencing curriculum implementation in traditional and conceptual classes. Teacher conceptions, which made up the units of analysis referred to the qualitatively different ways four university professors understood chemistry teaching. The categories resulted from an interpretative analysis involving constant comparative and triangulation research techniques.

Development of a grounded theory is accomplished by isolating categories of data which center on the participants, generating theories from the data, and gathering supporting evidence. My analysis began with a selection of classes tentatively classified as traditional or conceptual based upon student attrition rates and an intended curriculum. As mentioned earlier, a significant outcome of traditional teaching, extensively documented in the literature, is high levels of student attrition. In theory, at least, constructivist forms of teaching should improve learning outcomes and attitudes and, consequently, course completion rates. Therefore, the courses should be distinguishable by using recorded attrition rates and the intended curriculum. During the pilot phase, the courses were initially selected on the basis of these criteria. The pattern of teacher conceptions that lay behind the curriculum would remain covert until later in the study.

If teacher conceptions of teaching influence their decisions about the content presented and the strategies employed to represent it, then it should be possible to determine some aspects of their conceptions by observing the content, activities and strategies chosen and the reasons

given for the choices. An interpretative analysis to address these areas began simultaneously with data collection. Qualitative research techniques used for grounded theory generation consisted of examining the data for regularities and patterns and obtaining data from a variety of sources to support or refute the emerging patterns of teacher behaviors. These techniques involved semester-long participant observations in the classrooms and extensive document and record analysis.

My initial reviews of transcripts and field notes suggested consistent, observable differences in at least four areas of teacher behavior in traditional and conceptual classes. These categories, which were initially descriptive in nature, related to topic content organization, content representations, classroom social interactions and content testing methods. Appendix H contains the coding system used to identify behaviors associated with each of these areas.

Patton (1989) described the process of theoretical category formation as a form of inductive analysis in which data are collected and analyzed simultaneously and which can determine the direction of subsequent data analysis. For example, the data collected from observations helped streamline the process of interviewing with questions that focused on the emerging patterns. The focused interviews helped insure construct validity of the inferences made as the transcripts and field notes were systematically scoured for disconfirming evidence such as explanations or documents that contradicted the identified pattern (Erickson, 1986).

As the pattern became better defined, theoretical constructs were formulated based upon the collected data and the research literature,

which linked the empirical categories of observation with the more theoretical aspects of knowledge representation and acquisition.

Formal interviews were conducted with each teacher with the objective of describing as comprehensively as possible the emerging pattern of their conceptions of teaching. The questions were focused on the teachers' assumptions about subject matter and student learning in chemistry (see Appendix I). The resulting categories denote teacher conceptions. Supporting data which justify and support these categories are offered in the text and appendices.

Quantitative Analysis

Quantitative data were collected and analyzed at both student and section levels during the study. Student-level data were collected by research instruments which included pre- and post-responses to conceptual and quantitative questions on the chemistry test and an item analysis of attitude questions (post only). Student-level data were aggregated and mean scores were calculated for both the chemistry and attitude tests. An analysis of covariance was conducted on the chemistry posttest scores (Appendix N includes the ANCOVA source table).

Section-level data, provided by the Chemistry Department, included final examination item analysis, calculated as percent response to multiple choice items, class averages and standard deviations, and section enrollment figures from which percent attrition was calculated. Mean percentages of correct responses for qualitative and quantitative questions were derived from the final examination data and were utilized for class-level comparative analyses.

CHAPTER 4
RESULTS AND DISCUSSION
Teacher Conceptions and Practices

Science teaching involves strategies and methods that are intended to help students learn science content. The nature and scope of these methods vary among teachers and depend upon a number of factors which influence teachers' curriculum and instructional decisions. Among these, teacher conceptions of student learning and how content should be taught constituted a significant influence in the curriculum implementation process (Hashweh, 1985). In this study teacher conceptions were associated with differences in how a written chemistry curriculum was enacted. Differences were observed in the selection and organization of course content, in how content was represented during instruction, and whether in interactive or noninteractive formats, and in the methods employed to evaluate learning.

The pedagogy of traditional chemistry was highly consistent with didactic conceptions of learning as an essentially passive process involving the direct transmission of knowledge from teacher and text to students without regard to student preconceptions or misconceptions. The selection and sequencing of content appropriate for classroom presentations was indicated by the logical organization of chemistry established by the course text and syllabus. Learning was understood as the accretion of content knowledge, presented sequentially, and evaluated largely in terms of the acquisition of discrete problem solving skills and the capacity to decode mathematical symbolism. Correct solutions to exercise problems provided evidence to teachers for the success of their traditional methods.

By contrast, conceptual chemistry can best be described as a form of guided constructivism somewhere between pure didactic and pure discovery methods. It drew upon different constructivist conceptions of the development of scientific knowledge including the use of analogies (Clement, 1993; Brown, 1992) hypothetico-deductive reasoning (Lawson, *et al.* 1993) prior knowledge and conceptual conflict (Strike and Posner, 1985) and social constructivism (Vygotsky, 1978). In practice, it was observed to be more structured than discovery teaching, but less so than didactic methods. Conceptual chemistry methods incorporated a level of social interaction in the classroom that simply did not exist in the traditional courses, although the focus was on content goals, instruction and assessment methods as determined by the teachers. Conceptual chemistry was designed to help students construct theoretical models used in explanation, prediction and problem solving. It employed methods that interacted with students' prior knowledge by using various types of analogies and explicit instruction to promote the acquisition of concepts in agreement with accepted chemical theory and to identify misconceptions that were not. The teacher-student and student-student interactions helped teach students how to reason qualitatively with these newly acquired concepts.

In summary, the methods employed in conceptual chemistry included organizing the course around key concepts, instruction that featured multiple, qualitative representations of concepts, classroom interactions and the use of variable assessment practices to monitor learning.

In the first part of this chapter, overviews of conceptual and traditional classes are provided which relate teachers' conceptions to their

classroom practices in enacting the chemistry 1202 curriculum. Teacher conceptions, simplified in the form of summary propositions, are followed by supporting excerpts from interview transcripts and descriptions of classroom practice based on participant observations. The fact that teacher conceptions could be linked to their decisions concerning curriculum organization, instruction and testing helped to validate the initial classification of the classes either as traditional or conceptual. This was made possible only because teacher responses to interview questions and classroom observations of their strategies and actions were in close agreement; that is teachers taught in ways that were consistent with their conceptions of teaching. Table 4 provides a summary of the characteristic differences. However, the differences are framed in abstract terms that apply across all course topics. In the next section of the chapter, these generic propositions are reformulated in terms of equilibrium theory. This provided a content-oriented example that frames teacher conceptions in terms of topic content that is understood in different ways.

Teacher classroom practices are not homogenous masses of classroom activities. They possess definite structural characteristics that can be observed in the various ways course content is organized and presented for teaching. The content topics and strategies for teaching are thus linked in a pattern as teachers assemble the various topics, materials and plans - the components of lessons - into a pattern for instruction and assessment that is largely consistent with their understandings of content and pedagogy.

In the traditional classes this organization was a given, established by the text and syllabus and teacher assumptions about the logical structure of

Table 4
Comparison of teacher conceptions and practices

Traditional Chemistry	Conceptual Chemistry
<p><i>Learning understood as being linear and sequential in nature and resulting from accretion of perquisite knowledge.</i></p> <ul style="list-style-type: none"> • The traditional chemistry curriculum was organized around discrete topics as indicated by syllabus and text. Topics were presented sequentially and usually not related to previously taught material. Emphasis was on breadth rather than depth of coverage. 	<p><i>Learning understood as being holistic in nature and resulting from fitting knowledge into a pattern.</i></p> <ul style="list-style-type: none"> • Conceptual understanding was the basis for the organization of the conceptual chemistry curriculum. Topics displayed a highly efficient and interrelated structure that connected well with previously taught material. Emphasis was on depth of coverage and focused on key concepts.
<p><i>Knowledge as represented in verbal and mathematical modes.</i></p> <ul style="list-style-type: none"> • Instruction was fact oriented; that is, chemistry content was represented largely in the form of verbal and mathematical arguments via deductive analysis from empirical evidence. 	<p><i>Knowledge as represented in visual, verbal and mathematical modes (multimodal).</i></p> <ul style="list-style-type: none"> • Instruction consisted of enriched representation and elaboration of knowledge rich in depth and organizational quality. Content was frequently represented in the form of qualitative explanations and analogies expressed verbally and visually through graphics and demonstrations.
<p><i>Learning understood as a process of receiving knowledge transmitted from teacher and text (reception).</i></p> <ul style="list-style-type: none"> • Instruction emphasized almost exclusive use of the expository lectures with little or no dialogue among participants. Students were individually engaged in note taking and quantitative problem solving. 	<p><i>Learning understood as a process of knowledge construction as new information is related to prior knowledge through interactions with curriculum, teacher or students (interaction).</i></p> <ul style="list-style-type: none"> • Instruction emphasized active engagement of students in employing qualitative conceptual representations to construct explanations, predictions and in problem solving.
<p><i>Assessment of knowledge acquisition understood as a unitary process. All learning steps could be exhaustively and completely measured by standardized testing.</i></p> <ul style="list-style-type: none"> • Traditional testing in chemistry assumes implicitly that problem solving is equivalent to understanding concepts; therefore, tests consisting of quantitative problems assumed to measure acquisition of both prerequisite skills and concepts necessary in problem solving. Assessment methods provided evaluative feedback to students. 	<p><i>Assessment of knowledge acquisition understood as multiple processes.</i></p> <ul style="list-style-type: none"> • Assessment methods provided both descriptive and evaluative feedback to students. Involved standard tests, homework, question and answer sessions.

the topics. In conceptual classes the teachers reassembled the curriculum components into a different organization based upon the objectives of enhancing students' conceptual understanding and their capacity to qualitatively analyze chemistry problems. Information regarding students' cognition - their prior conceptions and learning difficulties - was essential to this organization.

The Traditional Chemistry Curriculum

Behaviorist theory assumes that learning is sequential and cumulative and that understandings occur by the accretion of elemental prerequisite knowledge. The essentially linear aspect of behaviorist learning theory is suggested by the use of learning hierarchies which sequentially order the necessary components leading to higher terminal objectives. This assumption also parallels the account of the structure of scientific knowledge given by earlier philosophies of science. Science has traditionally been taught in a linear fashion. For example, traditional texts organize important concepts and principles into different chapters. Teachers test on the chapters and reinforce learning of topics unrelated to one another (Bunce, 1996). Consequently, students are often left with seemingly unconnected and disparate pieces of information. The implications of this traditional conception of teaching are conveyed by Hoffman's use of the metaphor of a brick wall to describe his course curriculum: learning chemistry is like constructing a brick wall, built brick upon brick. It is not possible to lay the top bricks until the bottom ones are in place.

Hoffman: The second semester of this introductory course covers nine topics as outlined in the syllabus (additional topics will be taught if time permits). These topics belong, with a few exceptions, to the general area of physical chemistry. As you will see, there is quite a bit of emphasis on a quantitative description of compounds and processes. Teaching chemistry is not unlike building a brick wall, where one brick rests upon another.

The course syllabus which prescribed the content to be taught and the sequence to be followed was a significant influence in his course. Students would become more literate (in terms of formal chemistry) by virtue of

their adherence to the text and meeting the unit's learning objective. Once covered, the material was rarely revisited.

Throughout the semester Hoffman closely followed the organization of text and syllabus. This defined the logical sequencing of information that constituted the structure of formal chemistry which students needed to make an effort to learn.

Hoffman: It's ultimately between the students and the book. Of course, the more difficult concepts need to be explained and that's where I see the role of an instructor as someone who helps them in working problems. Of course, this requires that students make an effort in learning before they come to the classroom. That way I'm aware of the difficulties and that is the most economical way of teaching and the way one can answer any specific question.

The course sequence of topics, while closely adhering to the syllabus and text, was detailed and elaborated with careful definition, orderly, logical arguments and numerous examples of problem solving.

The traditional content and organization of the syllabus and text was influential, although more problematic to Reed than Hoffman. Reed's comments are noteworthy in that they appear to reflect a shift from an earlier epistemic commitment to the traditional structure of the curriculum.

Reed: I have adjusted the (1202) course but no one told me that there has to be a certain percentage that pass. It's the standard dilemma that a science teacher has. Should you teach to the median of ill-prepared students so they will get something out of the course or do you stick more to a pre-determined syllabus of what, by golly, you told the course's curriculum committee that the course is going to cover and include....and there's no right or wrong answer to that....it really depends on the philosophical values that you hold. However,

for whatever philosophical reasons, the reality I have to consider is that I have two hundred or so students out there that have whatever preparation they have for whatever reasons they have it, so I need to do the best I can do for the majority. I'll probably lose some of the better students.

Traditional Chemistry Instruction

The traditional view of scientific explanations is essentially a deductive process in which a proposition is explained by being deduced from scientific laws or statements of initial conditions, i.e., deductive procedures yield prediction and explanation. This process of scientific reasoning is also inherently sequential in nature (Holland, Holyoak, Nisbett and Thagard, 1986). The traditional teachers transmitted content in the form of verbally presented deductive arguments, explanation and as problem solving exercises based on examples from the text. Aside from occasional blackboard sketches, visual images were rarely employed to break the pattern. The traditional teachers apparently assumed that those students capable of deductive reasoning would assimilate the verbal and mathematical pattern of arguments and use this pattern to acquire the more abstract, theoretical concepts. This pattern may be closely related to the idea of a conduit in which teachers transmit knowledge to students. The acquisition of science knowledge is then understood as a result of the direct assimilation of information generally presented in hypothetico-deductive explanations by teachers. Whole class, noninteractive formats insured the coverage of the necessary content.

Hoffman's classroom instruction exemplified the expository lecture format, and he tended to teach by deductive arguments and textbook

problem examples, solving one after another on the blackboard. He explained the basis of his choice of this instructional strategy in response to my question concerning the introduction of a new topic or concept.

Hoffman: Give an example. It's the best way to go. If it's a demonstration then that's simple and I like to do that, but it's awfully difficult because we really don't have the facilities in these rooms to do demonstrations. Sometimes you can relate it to an everyday example. But the book has numerous problems as examples, so I say look here, look at this particular problem and I review these problems before I go into the classroom and if it illustrates the principle, well, I'll use that.

Hoffman did not normally do demonstrations or otherwise deviate from the lecture-chalkboard format. However, my field notes indicate that on at least one occasion, he began class with an overhead transparency. This was of an electrochemical cell and it served to initiate the topic of electrochemistry and batteries. Normally, he employed no visual aids, preferring instead to illustrate a concept or principle with one or two graphics hastily drawn on the blackboard. This was sometimes done in conjunction with the lecture topic or during a problem solving exercise. Homework assignments consisted exclusively of reading assignments and problem sets from the text. The homework was not graded or taken up.

The facts-before-thinking assumptions of didactic teaching also offer no reasons why students' preconceptions should be considered in instruction. This clearly was not a critical factor in Hoffman's conception of learning and it did not seem to influence his teaching. One result of this was that he did not specifically plan for or address students' misconceptions or learning difficulties, but felt that presenting the scientifically correct

information should be sufficient. Since learning resulted from student effort, a failure to learn was viewed in terms of lack of concentration or students not doing the assignments. This is indicated in his response when asked specifically why students failed to understand the material.

Hoffman: They probably were absent from class when I presented it or they haven't been keeping up.

In Hoffman's class, teacher-student interactions were limited to spontaneous questions and answers on the material just covered or in response to his inquiries about the homework problems. He did not otherwise solicit student ideas or opinions during class. For approximately 90% of each class period, students were individually engaged in taking notes and working problems from the board and/or text. No formal social structures were established, although several students indicated that they had formed study groups outside of class. Students who had difficulties with the subject matter that could not be addressed in class, were referred to the Department's tutorial lab and teaching assistants. Hoffman's time outside the classroom was limited.

Reed also used didactic forms of teaching. The chapter content was generally presented in verbal or mathematical form using the blackboard, Graphics, tables and diagrams from the text were explained, and sometimes sketched, but the emphasis was on problem solving. However, Reed was confronted with the dilemma of competing conceptions of teaching. Apparently he had attempted to accommodate his experienced-based understandings of student learning characteristics with his prior conceptions of chemistry pedagogy. While Reed employed the traditional

expository lecture format and testing practices, he espoused more student-centered views of learning. This was evident as he addressed the role of the text as a context for traditional pedagogy.

Reed: I don't think (the course) is conceptually as difficult as a lot of the other science students take. I think it's probably more the way we teach it and the books we write. Look at those books over there (referring to his office bookcase). They're monstrously thick. That book for example was written by Linus Pauling when I was an undergraduate. It's no bigger than this one (picks up course text). They keep turning out bigger and bigger texts each year. It's terribly intimidating to a student. When I retire I'm going to write a small chemistry book.

Reed's notion of student learning also included analogical reasoning. This was sometimes incorporated into his classroom lectures as a pedagogical principle.

Reed: I really believe the best way we learn just about anything and that applies to you and me as well as the students is by analogy....so whatever the topic is I try to fool the students into believing it's very much like something they already know how to do. This way they will develop a positive attitude about it as well as be able to do it. An analogy is the easiest way to learn something. I've made my course more informal, less structured along the old German line of mathematical logic, which was mainly proving theorems. Now it's more conversational, more related to everyday life...it's more learning by analogy than by 'here's the general principle and here's an application of that principle'...more laid back, I guess, because I can keep their attention better. We really don't have, still don't have, enough chemistry in our chemistry courses. General Chemistry is still taught as elementary physical chemistry.

Beyond these concessions to cognitive theory, however, Reed remained essentially committed to traditional practices. His lecture was pretty much a matter of delivering content knowledge to students through explanations

of empirical research and examples of problem solving. Analogies were sometimes used in the context of a problem explanation. Students spent the class period taking notes and individually calculating the answers.

I concluded that when confronted with two competing conceptions of teaching, Reed had maintained substantial elements of the old, while incorporating selected elements of the new.

Traditional Chemistry Assessment

One of the long-standing axioms of traditional teaching in the physical sciences is that a students' ability to solve a quantitative problem is equivalent to an understanding of the concepts that lie behind it. For many traditional teachers, this means that if students are able to achieve the computational goals of the course, there is no need for further understanding of students' knowledge or to facilitate students' growth in conceptual understanding. These assumptions reflect the influence of behaviorist theories on traditional testing practices.

Shepard (1993) has noted that in applying the criterion-referenced model of learning, test items are assumed to be an instantiation of a learning objective and therefore to measure all the prerequisite learning steps leading up to mastery of the objective. It is not then considered possible for a student to function well, i.e., solve a problem successfully, and not to have mastered the intended prerequisite skills and concepts.

Consistent with behaviorist assessment theory, Hoffman tended to equate student learning with test results, and more specifically, with a student's ability to solve problems. Of the four chemistry faculty who participated in the study, he alone expressed the view that quantitative

problem solving is an acceptable test of students' conceptual understanding of chemistry.

Hoffman: Well, (quantitative problem solving) is certainly a test of their understanding, but I don't think it's the only test. You could have conceptual qualitative problems that test the same concepts. Students don't like solving numerical problems all the time. It can be very boring. But they're necessary. They must be able to do it in Chemistry.

In practice Hoffman's assessment methods were basically limited to standardized multiple choice exams. He administered four such tests during the semester, dropping the lowest grade as seemed customary. Students were tested primarily on their problem solving abilities, and despite his reference to qualitative problems, the emphasis was decidedly on calculations in Hoffman's tests. He also utilized pop tests which invariably consisted of one or two quantitative problems. He indicated that these served to motivate students to attend class and to make an effort to stay up with the material. These test grades were factored into the students' course average.

In response to the question concerning class understandings of topics after instruction, Hoffman replied:

Hoffman: I think around ten percent. The rest are hanging in by their fingernails. But that's the group that toward the end of the course might pick it up. Many of them don't see it happening at all and they then drop the class. But every year I see a number that do badly on the first test but then they steadily improve. Others start in the 70's range and then drop steadily during the course and sometimes don't make it.

Hoots (1992) observed that science has been often isolated as an elitist domain, intelligible only to the initiated, dedicated problem solver.

Hoffman elaborated on this theme as he commented on the need to select the top tier students.

Hoffman: You see, not everybody's cut out for the college level. I would say in the United States, say 50% of (secondary) students go on to college. In Europe, it's about 10 to 15 percent. They're much higher level students....because they've been selected, and many students here with a high school diploma believe they can go through college and that's not so. You have to have certain abilities...and that's only for the top 10% to 15%. Take the top 10% to 15% of the United States and they probably would do very well in the European system and they'd love it.

Department records indicate that Hoffman's classes had attrition rates in the 60-70 percent range, the highest reported from all sections of Chemistry 1202. The top-tier students could be selected for professional careers through exams that, above all, indicated mastery of problem solving skills. Expected learning outcomes were expressed as follows.

Hoffman: I think students become more mature (after taking the course). They realize it take time and they realize one has to be wise to conquer chemistry...and just as I said before, studying the evening before doesn't do. It takes constant work....and they become more mature in the process.

Reed's homework assignments, which were usually lengthy, consisted primarily of problem sets from the text. These problems were usually discussed and worked out in class, but homework was not collected or graded. Reed explained that the homework assignments, although not a direct factor, were an extremely important indirect factor in students' grades. Since the problems were often worked through in class, students who attempted them had the added advantage of Reed's explanations and problem solving. However, students with continuing difficulties were

usually referred to the Department's tutorial lab, where teaching assistants were available to provide assistance outside of the normal class hours.

Reed conducted four, one-hour tests during the semester. His tests usually contained an approximately equal mix of qualitative and quantitative problems. Reed's response to my question concerning the equivalency of understanding with quantitative problem solving also suggests some change in his assumptions regarding testing.

Reed: The time was when I would have agreed with that one hundred percent. But I don't guess I agree with it as much anymore. For one thing, students are just scared to death of mathematics. It's more of a barrier to their understanding chemistry and if you let it be a barrier then they're not going to learn any chemistry.

The lowest grade on the four course exams was automatically dropped, while the other three were averaged to determine a student's course average. The course average comprised two-thirds of the final grade, while the Department final exam represented the remaining one-third.

Reed judged most students had attained an acceptable level of skill and conceptual understanding of general chemistry after completing his course.

Reed: I think about fifteen percent might be considered remedial in my expectation after the course...and these would be primarily in mathematical areas. The rest would have enough knowledge and skill for the demands that I make on them...but not for the demands I used to make on them.

Reed still had lingering concerns about watering down the course.

The Conceptual Chemistry Curriculum

The prescribed Chemistry 1202 curriculum did not fit the theories of learning or the curricular goals and objectives of the conceptual teachers.

From their perspective conceptual understanding was facilitated by an organization of concepts not present in the organization of the curriculum and text. An overt organizational scheme was constructed to address this pedagogical deficiency. The reorganized curriculum identified the course's key theoretical concepts which became the central, organizing constructs for each topic. The structure of each lesson was organized around those central concepts with supporting concepts drawn from related topic areas, often from previous chapters. Different curriculum units were connected to insure that students understood the interrelatedness of concepts and principles.

Henry's teaching experiences led him to realize that students experience significant conceptual difficulties at a qualitative level in addition to the challenge of learning quantitative concepts. His objective of emphasizing the key theoretical concepts can be understood as an attempt to have students build up their understanding at a qualitative level before attempting to master the quantitative concepts of formal chemistry. Henry's redesigned curriculum included activities and content which supported conceptual and pre-algorithmic thinking to create learning experiences which were meaningful to the student, yet which remained recognizable to chemists as scientific in nature.

Historically, courses in the physical sciences have tended to survey the discipline, covering as much content material as possible (Gold, 1988). Henry's method taught a limited number of topics, but they were treated in some depth. This required that some topics listed in the syllabus be given less emphasis, although there were never entirely excluded. As a practical

matter, he attempted to strike a balance between his emphasis on the key concepts and the demands of the Department's curriculum committee.

Henry: Most professors still can't get out of the mind set that we have to teach them everything in the textbook...Because we have to teach so much, we don't have time to explain the key concepts that the average students need to begin to really understand chemistry.

Consistent with constructivist conceptions of teaching, Henry's basis for organizing course topics was principally the development of student conceptual understanding, not the prescriptive presentation of formal chemistry. The text served primarily as reference material in Henry's classes.

Collins followed the organization of topics established in the class notes with a few adaptations and modifications of her own. Henry's notes were acceptable to her because of the high degree of compatibility in their pedagogical conceptions. She described her course objectives in these terms.

Collins: Basically it's to help the students develop an understanding of the concepts. I know that they don't know them on the level that chemists do. My teaching objective is really to help them incorporate some of the chemistry concepts into their knowledge base. I think that's going a long way. I'm always thinking of new ways to get the information stuck in there given the various types of students I have. There are certain concepts you want them to take away from the course. We do have a new text which I hope will reinforce that approach. It takes a conceptual approach. For example, it starts chapters with pictures of molecules.

In Collins' conception of teaching, the text supported the development of students' conceptual understanding but did not necessarily provide the basis for selecting and organizing topics for instruction. As in Henry's class, it enjoyed reference status, but was referred to more frequently for homework assignments, including additional reading as well as problem sets.

Conceptual Chemistry Instruction

Constructivist views of learning suggest that understanding involves more than the pattern of deductive prediction in generating an answer. To explain in the context of cognitive theory in to fit an idea into a pattern and deductive reasoning may not establish a sufficiently rich pattern.

Lawson (1993) stated that the pattern for theoretical concepts, by definition, cannot be directly experienced.

... for example, one cannot see molecules colliding with and sticking on or bouncing off each other. Therefore, to help students experience and dissembled the pattern, some sort of analogous human-level experience, which embodies the pattern should be provided... (p. 1074).

Some researchers suggest that analogical reasoning may be a primary source of the theoretical component of scientific thought as well as a way to promote theoretical concept acquisition and conceptual change.

Henry's conceptions of chemistry teaching included the use of nonformal methods that could be used to reason qualitatively about chemical concepts and processes. The theoretical view that guided development of his classroom instruction was that analogical processes are central to qualitative, conceptual reasoning and are an important complement to student understanding of the more formal and mathematical aspects of chemistry. Thus, many students receive more information and understanding from the inclusion of visual analogies and images (pictures, graphs, demonstrations) than from verbal material alone (written and spoken words and mathematical formulas and equations). The approach used in both Henry and Collins' classes focused on the development of qualitative understandings of abstract, theoretical concepts

through the use of analogical reasoning as a central technique. In this way the method departed from purely didactic methods and from a model of knowledge piped directly into an empty vessel (Clement, 1993).

Consistent with his constructivist model of learning, analogies were used to draw out students' prior knowledge and interact with it in a number of ways. Students were then taught how the concepts could be applied in explaining or predicting chemical phenomena.

Henry: The lecture has to be designed so when you introduce a key concept, you've got to hammer it into them in ten different ways. You use graphics, you do a demonstration, you show how it applies to something they already understand. If you don't connect it with the real world, then they are not going to understand it at all. Basically, I'd rather give them the concept, get them to understand it, and then let them discover how to use it ... how to use it in making predictions about chemistry.

In presenting new information, Henry typically used an initial, qualitative representation of theoretical concepts and principles followed by a quantitative application. Problem-solving algorithms were well-illustrated in the class notes and reviewed in class with multiple numerical examples worked out in an explicit, step-wise fashion. This is a prescriptive approach to problem solving that specifies essential features of procedural skills (Reif, 1987). Henry rarely deviated from this instructional format.

His conceptual instruction, which made heavy use of visual analogies can be understood as a strategy to make abstract concepts accessible given the constraints of time and the variability of student learning characteristics in large lecture classes. The approach contrasts with the more time consuming inquiry methods that promote concept acquisition by inductive reasoning.

Henry: The discovery-based approach is basically that you let the students discover the information 'like scientists do'. The discovery-based approach, however, is extremely slow. Now granted, it's very effective, but one reason it is so effective is because it is so slow....we don't as a practical matter, teach that way, so you're not really going to do things (in lecture) like we do them in the research lab. I'm convinced that the way I teach lecture is as effective as any discovery-based approach I've heard of. About ten percent of the class understands a concept the first time I bring it up. When I'm done with the concept in lecture, I think it's up to about sixty to seventy percent.

Time was an important constraint on conceptual teaching for Collins. Henry's class notes were adapted to her course, in part, to make more efficient use of it during class periods. Her decision was, no doubt, influenced by her years of prior school teaching experiences at both the secondary and college levels.

Collins: When I first began teaching and using transparencies, we spent a considerable amount of class time with students scribbling down everything I said. I thought the idea of *das* notes was an excellent one. Students wouldn't be preoccupied with copying notes, but would have more time to listen and be actively involved in the lecture.

Collins and Henry shared not only the class notes, but a number of classroom practices and much of their theories of teaching and learning. As with Henry, the students were a powerful context for her teaching. Unlike Henry, she seemed to be linked to supportive communities of college science educators that were exploring new ways to teach science. On several occasions, she mentioned the results of workshops and meetings that dealt with various aspects of college science pedagogy. I suspect this extra-departmental context was also an important influence in shaping her teaching practices.

Collins' cognitive conceptions of learning were underscored by the importance of students' prior knowledge in planning her classroom presentations.

Collins: I try, if it's something that's brand new to relate it to what they already know...and that's not always easy in chemistry. But as a learning principle, students have to relate new information to their current knowledge and to interpret it.

Like Henry, her classroom presentations were invariably accompanied by visual aids and graphics, but it was the classroom chemical demonstrations, or simulations, as Collins referred to them, which were most memorable. These were vivid visual analogies that were accompanied by detailed explanations that left little doubt as to what microscopic chemistry should be linked to its macroscopic manifestations. On one occasion, during a session on the topic of chemical kinetics, she used an iodine clock reaction accompanied by a tape of Tchaikovsky's 1812 Overture and a number of student volunteers. A semester later, I would still encounter the occasional student who would recall the vivid, oscillating color changes in a series of beakers synchronized with the cannon booms.

Collins: I believe that adding the visual aspect enhances student understanding of the abstract concepts in a way that can't be done by lecturing alone. It's really adding another dimension to learning. Listening is a very passive mode. Adding visuals and simulations for what I believe is a very visual science...it's basically a picture is worth a thousand words.

Classroom Interactions

Students construct meaning through interactions with teachers, classmates and curricular materials. However, not all interactions contribute

to the construction of scientific meaning. Interactions that promote a dialogue between participants and employ accepted scientific understandings can facilitate the construction of new meaning from pre-existing ideas (Vygotsky, 1978).

In conceptual chemistry, the social environment was structured by organizing whole-class and small group interactions where question and answer sequences occurred. Consequently, the amount of class time students spent in social interactions was increased while individualized engagement was decreased.

In Henry's class, study groups were formed, each named for a chemical element, and with shared responsibilities for homework, class recitations, and in general, learning chemistry. Individual and group incentives (bonus points) were used to encourage helping behaviors among group members, a strategy that has consistently found positive effects on student achievement (Slavin, 1983). For example, after laying the groundwork for understanding a topic, Henry would call upon his study groups to answer questions in front of the class, a process he described as designed to establish a strong qualitative understanding of a topic. This is consistent with constructivist learning theory which suggests that the likelihood of conceptual change is maximized when students are socially confronted with contradictions or confirmation of their current conceptions. Although he did not identify the process in exactly those terms, Henry apparently embraced the notion that scientific knowledge is, in part, constructed through social interactions that engaged students in reasoning with concepts and principles.

Henry: Well, you know, you're asking questions of the students which is something that isn't usually done in a big lecture format, but I find that's very important even though it slows down the pace of the lecture. You have to get them actively involved in some way for them to really learn the concepts.

Collins also emphasized active learning in all aspects of her classroom instruction. However, no formal study groups were established over the course of the semester. Instead, Collins favored frequent whole class interactions in which she would work through problem examples with her students. Students were encouraged to work with and assist one another during such sessions and I observed that students usually organized themselves to work in small groups in which there were high levels of student-student interactions. Collins also felt this further enhanced student understanding and encouraged cooperation rather than competition in learning. This process allowed her the opportunity to move around the classroom and interact with students, to monitor their work, and to address any procedural problems that might arise. She responded immediately to these through additional explanation or by reference to an overhead transparency that provided the appropriate concept or procedural step.

Collins: You can stand up there all day working problems, but unless the students work through them, they won't learn how to solve them. I encourage students to work through problems in class throughout the semester. I try to get around the classroom to see how well they're doing and to help out if needed. I do this as often as I can, but of course you have to keep the class moving along also. From the feedback I've gotten, most students feel it helps them understand the problems when they work together to solve them.

Informal interactions between students and teacher in the form of questions and answers were frequent. On occasion, students were asked to come to the blackboard to demonstrate successful problem solutions. Collins' use of student-teacher interactions to achieve her pedagogical objectives is an example of the dynamic nature of her classroom teaching practices.

Conceptual Assessment

A variety of assessment methods were used for evaluating students during the course. Henry gave three hour exams, as well as the comprehensive final. These in combination, made up 50% of a student's grade. The hybrid multiple choice/essay exams were designed to test for qualitative understandings as well as computational skills. Henry had formed definite opinions regarding traditional teaching and testing that he felt biased students toward computation and away from conceptual understanding.

Henry: From my teaching experience, I know students can memorize formulas. Memorizing formulas and then plugging the numbers in and getting a number out doesn't necessarily mean you understand anything qualitatively about it. However, some of my colleagues do believe this is the case. They believe that unless a student can do the math, they don't understand the concepts. I believe if you understand the math, and then can extend that, tie it into the physical and the qualitative concepts, then you have a complete understanding. I know a lot of math faculty who are mathematical geniuses, but they don't know any chemistry. That's why math professors aren't teaching chemistry -- it's more than mathematics. We've overemphasized the math if you consider that 90% of our students are never going to use these math functions again. The first thing they will forget are the mathematical

formulas, but the last thing they will forget are the qualitative concepts. We need to teach both.

The remaining 50% of a student's grade, some 200 points, could be earned by the 10 graded homework assignments, approximately one for each chapter covered. Students were encouraged to work in their study groups on the homework assignments with the stipulation that students turn in their own handwritten copy of the assignment. The routine of homework grading provided an important information gathering point as Henry charted his way through the course topic by topic. It seemed to provide for rapid course adjustments, if required, as was the case when he took time to address misconceptions or learning difficulties as they arose. The process of homework checking thus provided an empirical data base for his assessment of class understanding of concepts and problem solving. Additional points could be earned by writing a 2-4 page essay on a selected chemistry topic worth 100 points, the same as an hourly examination. The list of 65 suggested topics ranged from acid rain to zeolites, but Henry encouraged students to come up with their own selections as well. Additional points could also be earned, at the instructor's discretion, by the study groups' performance during class question and answer sessions.

Henry was accessible to his students, keeping office hours open for them and even extending an invitation to meet with them during the evening hours or on weekends, if necessary. Two help sessions were scheduled immediately prior to each examination. If that was not enough, he would make specific appointments to discuss problems with individual students or schedule an additional session if needed.

Collins monitored student understanding through the use of short quizzes which were administered at regular intervals. These exams typically required about 15 -20 minutes and provided her and the students with feedback on their progress. These mini-exams constituted 50% of the course grade with the mid-term and Department final making up the other 50%. The regular schedule of exams served as a strong motivator for students to keep up with the material in her judgment.

Collins' conception of learning in chemistry also rejected the equivalency of quantitative problem solving with conceptual understanding.

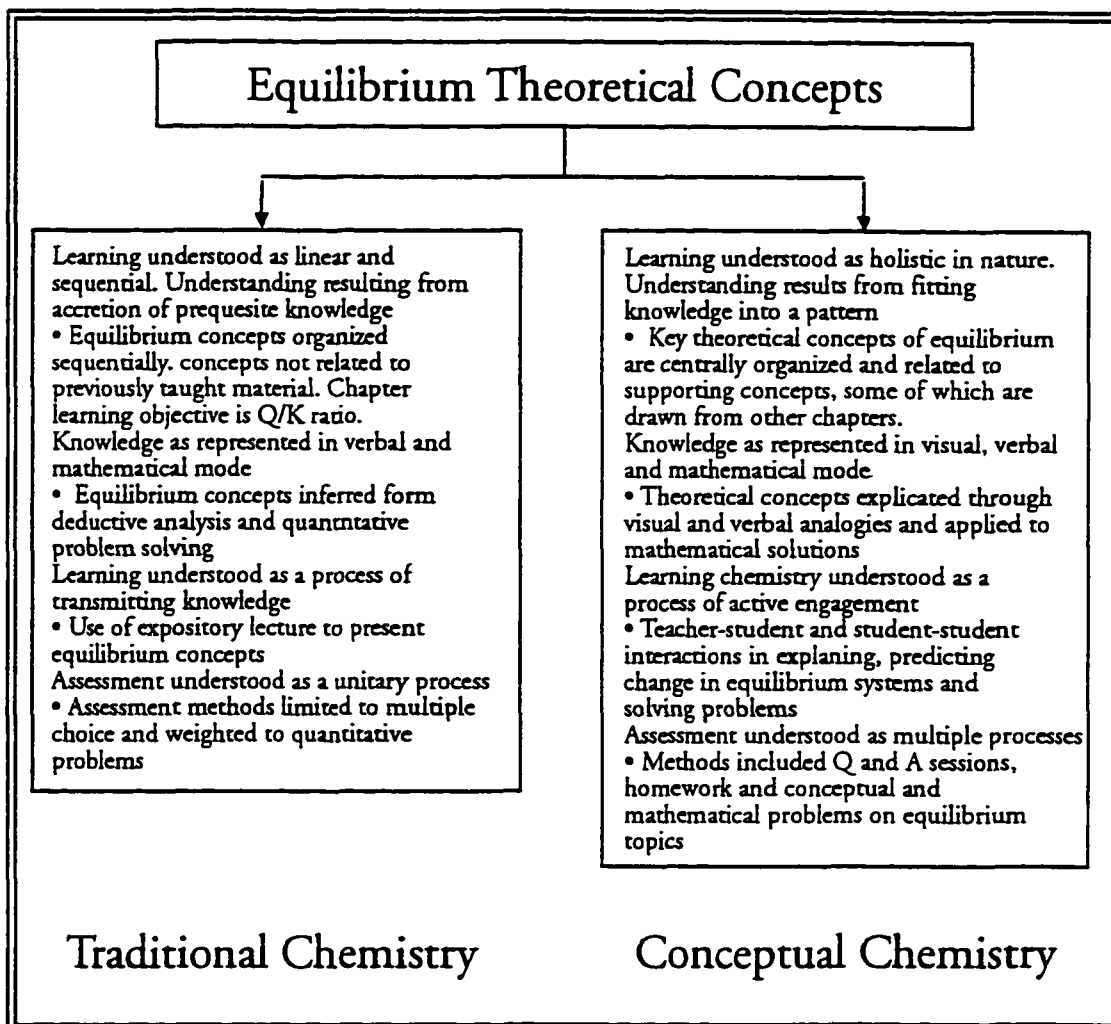
Collins: In my class when I don't give multiple choice exams, it's harder for students who don't understand to fake it. I sometimes give short essay questions instead of multiple choice to test their knowledge and understanding. I know from my own experience in teaching that students can memorize how to do problems and not understand what's going on behind the problem. I heard an interesting lecture on chemical education by a physics professor from Harvard. His students were acing his quantitative exams...and then he gave them a conceptual exam and they bombed it. He was amazed that they couldn't answer questions about simple concepts they had been tested on earlier...but that was only in a quantitative format.

Her interest in this type of research carried over into her classroom practices. It no doubt influenced her decision to allow my field testing questions for the research instrument subsequently applied to pre- and post-test conceptual and quantitative problem solving (see methods).

Chemical Equilibrium

The topic of chemical equilibrium demonstrates the application of traditional and constructivist conceptions in the teaching of the concepts of

Table 5
Equilibrium theory in traditional and conceptual chemistry



equilibrium theory. This section discusses and demonstrates how equilibrium concepts were differentially organized in the curriculum and how they were represented in both instruction and assessment. The excerpts taken from transcripts of classroom instructional episodes are included in the appendices (see Appendix C). These are generally limited to the first few minutes of teacher explanations and are always associated with the first introduction of a theoretical concept to the class. The visuals depicted are

those used by the teachers during their presentation and are taken from the blackboard or extracted from the class notes.

Organization: Equilibrium Theory

Figures 2 and 3 depict the organization of theoretical concepts of chemical equilibrium in the course curriculum of traditional and conceptual chemistry .

In the traditional classes, the structure of formal chemistry as defined by the text was the basis for organizing course content. The textbook represented the topic in terms of physical and mathematical chemistry. Chapter 17 contains a total of 34 pages, 27 of which contain descriptions of the results of empirical research of equilibrium systems complete with problem examples of basic principles. Five pages are devoted to strictly qualitative explanations of methods for understanding equilibrium reactions. The chapter content was sequentially organized in a logical progression of topics which culminated with the quantification of the theory in the reaction quotient.

The avowed basis for content organization in the conceptual chemistry class notes was student conceptual understanding, and the notes focused student attention on the theoretical aspects of chemical equilibrium. For example, approximately half of the section dealing with the topic of equilibrium dealt solely with development of qualitative understanding of concepts and the application of qualitative reasoning in problem solving. By limiting content to key concepts, the volume of information was also reduced substantially compared with the textbook's coverage.

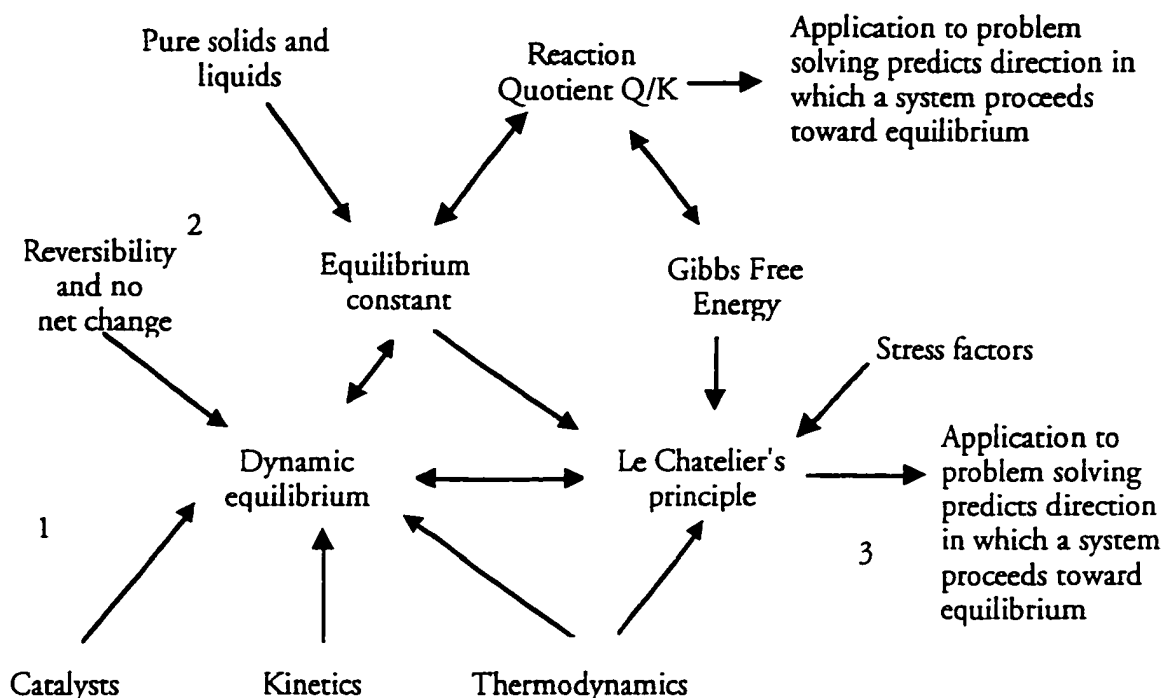


Figure 2
Organization of equilibrium theoretical concepts
in conceptual chemistry curriculum

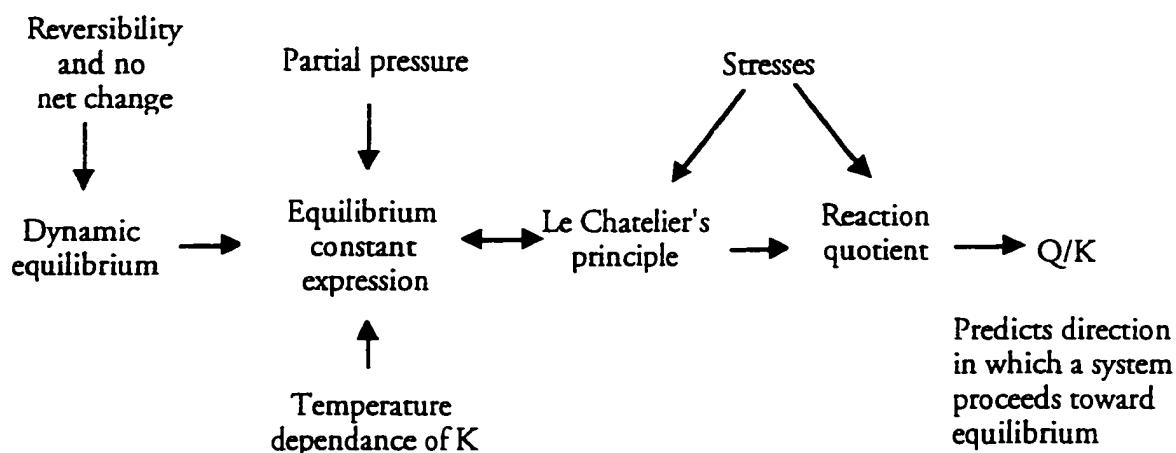


Figure 3
Organization of equilibrium theoretical concepts in
traditional chemistry curriculum

The courses' central organizing constructs included the theoretical aspects of dynamic equilibrium, Le Chatelier's principle and the equilibrium constant which were interrelated with supporting concepts. Because the content was organized around key concepts, the curriculum more closely resembled a conceptual mosaic than a sequencing of topics. For example, Le Chatelier's principle, a central concept was supported by explanations of thermodynamic principles and the concepts of entropy and enthalpy. These concepts were not included in the text's chapter on equilibrium theory, but were confined to discussions in previously covered or subsequent chapters. The principle was directly related to other central concepts including the reaction quotient and the dynamic equilibrium characteristic. In the traditional curriculum, dynamic equilibrium and Le Chatelier's principle were discussed solely in the context of the equilibrium constant and as a prelude to explanations of using the reaction quotient.

Instruction of Equilibrium Theory

Table 6 is a summary of the ways equilibrium theoretical concepts were presented in teacher classroom presentations (see Appendix C for complete transcripts).

Traditional instruction was frequently couched in terms of empirical data resulting from measurements of the processes of physical and chemical equilibrium systems, and lectures were grounded in singularly verbal and mathematical representations devoid of visual aids.

The theoretical conception of a dynamic equilibrium is of two opposing processes of molecular dissociation and recombination. When a chemical reaction attains equilibrium, both the forward and reverse

Table 6
Instruction: Equilibrium Theory

Theoretical concept	Traditional chemistry	Conceptual chemistry
Dynamic Equilibrium	Explanations associated with qualitative or quantitative analysis	Explanation associated with qualitative analysis and visual analogy
Equilibrium Constant	Explanations associated with quantitative analysis	Explanations associated with qualitative analysis
Le Chatelier's Principle	Explanations associated with quantitative analysis (Students individually engaged.)	Explanations associated with qualitative analysis and visual analogy (Students interactive in analysis and problem solving.)

reactions continue to take place at the same rates, although physical observations may indicate no measurable change in the concentrations of the reacting species. Hoffman's presentation involved interpreting the texts' kinetic profile which indicated that in any equilibrium system containing two or more species, the values of the ratio of products to reactants is constant irregardless of the amount of substances present. However, Hoffman's explanation was of an empirically based model which did not access the molecular concepts underlying these observations although they are implicit in his problem example and are treated in the text.

Hoffman: The constant value of the $[\text{NO}_2]^2/\text{N}_2\text{O}_4$ ratio at equilibrium ratio shows even if we start with different initial concentrations, we can logically enough arrive at a state of equilibrium (see Appendix C for full explanation).

Hoffman's students were left to infer that the value of the constant relates to the concept of no further changes in molecular concentrations over time, or that reversibility is suggested by starting with different initial

molecular concentrations on either side of the reaction and arriving at an equilibrium value.

Reed explained dynamic equilibrium by describing an example of phase equilibrium which he then related to the analogous situation occurring in gaseous equilibrium.

Reed: Anybody who has used nitric acid is familiar with the brown fumes. The fumes are actually a mixture of two kinds of molecules, NO_2 and N_2O_4 which change easily into one another. In the fumes, you have a situation very similar to the liquid vapor system except that here two compounds exist in the gaseous phase rather than one compound in two phases. If the equilibrium is similar, we have to assume that two processes are going on at the same time, a forward reaction and a reverse reaction. This is a dynamic equilibrium.

The explanation of the equilibrium constant consisted of a deductive analysis taken through successive steps leading to the mathematical formulation of the constant. This essentially replicated the way the pattern was originally deduced from experiential measurements of equilibrium systems. The concept was not otherwise explicated or linked to a molecular model which may have provided a way for it to be interpreted.

The chapter learning objective was the use of Q/K ratios as a mathematical quantity that would allow prediction of the direction in which an equilibrium reaction proceeds. The use of Q/K ratio values to predict an equilibrium shift is related to Le Chatelier's principle. However, the ratio is a more generalized quantitative function that does not presume an initial equilibrium state, while Le Chatelier's principle refers to a system displaced from equilibrium by a change in conditions. In the traditional classes, the notion of qualitatively predicting the effect of various factors

upon the position of an equilibrium was suggested only after demonstrating through several problem examples that it could be done by using a mathematical calculation. This approach was exactly opposite to the methods used by the conceptual teachers who explicitly described Le Chatelier's principle as a qualitative concept prior to a quantitative demonstration of the principle.

For example, the following excerpts from the transcripts demonstrates Hoffman's preference to teach the use of mathematical ratios to predict an equilibrium shift. Underlying theoretical concepts such as Le Chatelier's principle were implicit in his discussion but were obscured by his quantitative explanations.

Hoffman: If we start with a mixture of two gases and we want to know whether a reaction will proceed in the forward or reverse direction, the decision can be made if the concentration ratio is compared to that which has to be established at equilibrium. We can distinguish three possibilities by comparing Q to K . If $Q > K$, the reaction will go to the left or in the reverse direction. If Q equals K , then the system is at equilibrium. If $Q < K$, the reaction goes to the right.

After working through a problem example, (see Appendix C), Hoffman discussed the effects of a pressure increase on an equilibrium system.

Hoffman: This would make a good demonstration, but I can't do it for safety reasons. Let's suppose we put this into a container except that it is transparent so we can watch the color. Now we increase pressure and reduce the volume of the gases. When NO_2 changes to N_2O_4 , the number of moles is halved. If the volume is constant, the pressure depends on the number of moles present. Therefore, when NO_2 molecules combine, the pressure decreases. So when we increase the pressure on the system, the equilibrium shifts to make fewer moles of gases. The color changes from brown to colorless.

Hoffman did not identify Le Chatelier's principle as a theoretical concept during his discussion, and there was only a single instance in which it was even mentioned during his lecture.

Hoffman: When a system is at equilibrium and conditions are changed, the system adjusts to accommodate the conditions.

Beyond this, he did not indicate that it is possible to apply Le Chatelier's principle to predict an equilibrium shift without calculating a numerical value. Students were left on their own to discover how to understand and apply the concept.

Similarly, during the following narrative, Reed explained the mathematical basis of Le Chatelier's principle before identifying it in qualitative terms.

Reed: The mathematical quantity that looks just like the equilibrium constant expression, but is not necessarily the equilibrium value, is called Q . Q is equal to products over the reactants. If in our example you lower the pressure, the downstairs becomes smaller, so Q is now greater than K . As a result what has to happen is Q has to come down in value to equal K . For Q to equal K again, either H_2 pressure has to go up or methane pressure has to go down or both. Which reaction shift would do that? Shifting to the left makes more hydrogen, i.e., the H_2 pressure goes up. It also makes methane pressure go down. So, we conclude that the reaction shifts to left. Now, you'll notice that I didn't really use the Le Chatelier's principle. I just used a mathematical form of the equilibrium concentrations to figure out what had to happen. What I've done, in this case, is proven for you the mathematical basis for the principle.

The conceptual teachers assumed that many students could not keep pace with the volume and sequence of verbal and quantitative oriented explanations and problem solving in traditional chemistry. Their

representations of equilibrium theory can best be described as packets of interrelated, theoretical concepts presented in the form of physical and molecular analogies. Some research suggests that physical analogies may help in concept acquisition and conceptual change by defining the nature of the theoretical concept, but successful application probably requires hypothetico-deductive thinking (Lawson, Abraham and Renner, 1989; Lawson *et al.*, 1993). Indeed, the objective of this part of instruction was the use of analogical reasoning to define the nature of theoretical concepts. When a concept was understood qualitatively, it could then be applied in deductive explanations and problem solving -- not before. In his classroom presentations, Henry approached the topic of dynamic equilibrium with a formal definition accompanied by a visual aid. The visual employed a molecular analog to help address a common misconception and develop a qualitative understanding of equilibrium as a dynamic process for the students.

A common problem in the understanding of equilibrium theory among both secondary and college students is a failure to comprehend the dynamic equilibrium characteristic. Students frequently invoke a naive conception similar to the notion of a balance of weights in a scale and use this concept to infer that an equilibrium system represents a static balanced state. Henry addressed this problem directly.

Henry: The arrows show that this is a dynamic state. This is a very important concept that many students have problems with. It means that a balanced reaction has attained a state of equilibrium. The forward and backward reactions have not stopped. At the molecular level reactant particles collide and form products and product species collide and reform reactant species.

Collins' introduction of the topic also emphasized a molecular model.

Collins: The picture I want you to get is this: in this reaction the molecules of A collide with B molecules and form C and D molecules. The reaction proceeds at a certain rate which is r_1 . Now lets imagine we have the reaction in a closed container so molecules don't escape. What happens? When C and D begin to form, collisions occur between them – and they begin too reform A and B. This reaction is going on at some rate, say r_2 . so this means that the concentrations of molecules will increase too. Eventually, the rate of the reverse reaction will equal the rate of the forward reaction. A and B molecules will form at the same rate as C and D molecules. Then you have an equilibrium system. This is what this equilibrium means. Both forward and reverse reactions continue to take place at the same rate, but there is no change in the concentration of the molecules. O.K? Does everybody see that?

In contrast to the traditional teachers, the equilibrium constant was introduced by relating it to molecular chemistry. Henry later expanded his explanation to deal with a misconception that interfered with its use. Henry's classroom session on the equilibrium constant began with the conceptual basis for the mathematical expression.

Henry: Look at this slide. It shows a mathematical expression that you will be using a lot in your calculations. It is called the equilibrium constant and it is derived from the so-called law of mass action which says that the concentrations of reacting species are related to the rates of reaction. In the expression for the equilibrium constant, note that the products make up the numerator and reactants make up the denominator. Also, each concentration of the reactants and products is raised to a power equal to the number of moles of that species in the balanced reaction. The fact that it is possible to write an equilibrium constant which has a definite numerical value for an equilibrium reaction means that if we start with a mixture containing only molecules of reactants A and B, a reaction must occur to form products C and D, O.K? (see full explanation in Appendix C).

After introducing the equilibrium constant, Henry used the notion of molecular concentrations to explain why the values for solids and liquids are factored out of an equilibrium expression. During problem solving in introductory classes Henry had discovered that many students included them in their calculations, which almost guaranteed an incorrect solution.

Henry: A lot of students still don't understand why solids and liquids don't get involved in the equilibrium calculations. Let's go over them. I've used this example in my office a couple of times. (goes to blackboard) Makes a grid. Let's say each of these squares is one square inch. This is a little like what I do on my desk. Now put a penny in one of these squares. This is the concentration of pennies, the number of pennies per unit area. My unit area is one square inch or one of those boxes. The point is that concentration is very different than quantity. Basically, it is quantity divided per unit area. It's a three dimensional unit of measurement. So it doesn't matter if it's five millimeters of solution or ten liters of solution, the concentration of that solution is the same. It doesn't matter if I have one hundred pennies on the grid or ten, the concentration of the solution is the same. That's the way solids and pure liquids are. Solids and liquids have their molecules and atoms packed together as closely as they can get, and the concentration is always the same. It doesn't matter whether you have one gram of a solid or a hundred grams, the concentration of the molecules in that solid material is constant, like pennies on the grid. And the equilibrium constant, the equilibrium expression only depends on the concentration of the material, not the quantity. The concentration of solids and pure liquids doesn't change it's constant. Now, if I'm dealing with a solution, the concentration can change. If I dissolve something in a liter of water, depending on how much I dissolve, the concentration will change. This is true for solutions and gases, the concentration of particles do vary with volume or pressure and the amount of material we put in.

Collins also introduced the equilibrium constant by relating it to molecular chemistry.

Collins: Equilibrium constants have two important functions. They can tell us whether a reaction will be spontaneous under given conditions and in which direction. They also let us calculate the concentration of products and reactants at equilibrium.

It is important to remember when we talk about these math ratios to remember that a chemical equation tells us about reacting molecules. Whatever ratio exists between particles of reactants and products.... It also exists between moles. The mole really expands this up to lab-size quantities, O.K. When you compare Q to K_{eq} you can tell which way a reaction will go to reach equilibrium.

Although both teachers taught the students the use of Q/K ratios, Le Chatelier's principle was a central theoretical concept which organized much of their subsequent presentations on equilibrium theory.

Thermodynamic principles were introduced to give students a deeper understanding of its implications.

In the following explanation, Henry attempts to link abstract concepts to students' prior knowledge by using a visual analog which depicted containers filled with water. The linked containers were analogous with an equilibrium system. The model served to convey the concept that for a chemical system, the natural drive toward maximum stability is also the drive toward minimum enthalpy. Henry restated the concept in terms of thermodynamics. The container analogy anchors in students' prior knowledge and bridges to the target concepts of entropy and enthalpy.

Henry: Equilibrium is thermodynamics. If you know ΔG , the thermodynamic value of a chemical reaction – this gives you the amount of energy released and available. For example, if reactants are very high in energy and products very low, the thermodynamics require that you should go to products. This reaction follows the drive that nature favors, a decrease in randomness. The reaction occurs

spontaneously, like water flowing downhill. If reversed, you should have lots of reactants. Thermodynamics doesn't tell you how fast a reaction is going. That's kinetics. Thermodynamics tells you about the ratio of products and reactants. There is a general mathematical expression to describe this also which we discussed. It's called the equilibrium constant (K_{eq}). If $K_{eq} > 1$ we have more product than reactant., If $K_{eq} < 1$, we have more reactant than product. At a given temperature, this ratio is always constant.

Le Chatelier's principle was discussed and demonstrated over several sessions. As usual, graphics or demonstrations served as visual analysis and were accompanied by in-depth explanations to convey a qualitative understanding of theoretical concepts and principles.

Henry: Now we come to a very, very important point. This is perhaps the most important qualitative concept that you will learn this semester for chemical reactions. Listen carefully. We're going to do some numerical problems later, but what I really want you to understand and to be able to qualitatively predict is the qualitative concept and how it affects the performance of chemical reactions. It's called Le Chatelier's' principle, named for the French Chemist. When a system in a state of equilibrium is acted upon by some outside stress, the system will, if possible, shift to a new equilibrium position to offset the effect of the stress.

Various stresses were defined that affect equilibrium systems such as adding or removing reactants or products, increasing or decreasing temperature or pressure and volume if gases are involved in the reaction. These were presented as key propositions. Henry related the container graphic to the set of propositions to provide a conceptual framework for a qualitative understanding. In this way the key propositions were subsumed into the model for Le Chatelier's principle (see Appendix C).

Henry: (Referring to the container graphic) Now I'm going to disturb this equilibrium system. This represents $K_{eq} > 1$, we are making more

product than reactants, O.K.? Look what happens if I add more product – H₂O – now I'm getting a flow backwards so we're making more reactants but the same amount of energy exists.

This is what Le Chatelier's principle informs us qualitatively. Again, if I'm adding more reactants to the reactant side, I'm disturbing the equilibrium so the net reaction shift is to make more product. Now look again at the level in the two containers. It helps to understand if you relate it also to thermodynamics. If the products are high in energy, it will flow back to make more lower energy reactants. So if there's a big energy difference, you don't worry too much about the equilibrium system since it's already going to the side with the lower energy level. Remember, thermodynamics doesn't tell you how fast the reaction is going. Now let's think of temperature change. What happens depends on whether the reaction gives off heat or uses heat. If exothermic, heat is a product. Now increase the temperature. You add more product, so the equilibrium shifts back to make reactants. If you remove heat, it shifts forward. This can help you remember the key concepts.

Interactions with Equilibrium Theory

Henry's study groups were challenged to qualitatively predict the effects of various physical and chemical stresses on equilibrium systems. Such teacher-student interactions taught students how to apply their conceptual/propositional framework for Le Chatelier's principle to explanations and problem solving.

Henry: O.K. Let's go through these reactions. Study groups, are you ready? Let's start with Sulphur. (Referring to the overhead transparency) Is sulphur here? (Student responds) O.K. Look at the first problem. I think I would like to make more product. What would you do?

Student: Well, add more CO₂.

Henry: O.K. Let's think of Le Chatelier factors. What does that do to the equilibrium if I were to add more CO₂?

Student: It would increase the pressure.

Henry: Very good. Class, we increase the pressure. If you increase the pressure, you compress the gaseous molecules into a smaller volume.

The system responds, in this case, by shifting to make product. to favor producing the smaller number of molecules. O.K. Look at the same problem. Let's call on ... Phosphorous. Is Phosphorous here? (Student responds) What else can I do to this reaction to increase the products? Student: (after conferring with group) Lower the temperature? Henry: That's right. Why? Student: It has a negative ΔH so it's an exothermic reaction. It's giving off heat as a product. Henry: So what. Student: So by taking away the product, lowering the heat, you can cause the equilibrium to shift to the product side. Henry: Very good!

During her class session on Le Chatelier's principle, Collins introduced the concept with a graphic. Following this, she led her whole class through an exercise in qualitative problem solving, using Le Chatelier's principle in a manner similar to Henry's sessions with his study groups (see Appendix C).

Tests on Equilibrium Theory

Table 7
Assessment: Equilibrium theory

Traditional chemistry	Conceptual chemistry
Quantitative or qualitative/ quantitative problems in multiple choice testing format	Qualitative/ quantitative problems, essay writing, question and answers, interactive problem solving and graded homework
Tests of learning equilibrium provided evaluative assessment with minimal descriptive feedback to students	Multiple tests of learning equilibrium provided with evaluative assessment and descriptive feedback to students

Hoffman's emphasis on mathematical competency is apparent from an analysis of his test (Appendix E). Eight out of ten of his test questions required only calculations. Interestingly, despite his lack of emphasis on Le Chatelier's principle as a qualitative concept, there are two questions that asked students to use the principle to qualitatively predict the direction

in which an equilibrium will shift in response to changes in conditions.

Reed's test more closely resembles the ratio of qualitative and quantitative questions used by the conceptual teachers with about a 50-50 mix of each. However, this comparison is somewhat misleading as to its significance as a method of assessment. Both Reed's and Hoffman's assessments of student learning were essentially confined to standard multiple choice exams although Hoffman on occasion did use pop tests with quantitative questions. Neither employed the alternative methods used in the conceptual classes.

Henry's and Collins' conceptions did not include the traditional assumptions of assessment as a unitary process; that is, they rejected the notion that a single form of evaluation, such as problem solving could account for the various ways learning exists. At various times in the conceptual classes, conceptual understanding meant that students could construct qualitative representations of chemistry concepts and processes or reason about these processes using conceptual representations, construct mathematical or algebraic representations with the help of their qualitative understanding or solve the problem quantitatively. These objectives made it necessary to evaluate student understanding through multiple measurements. These methods included, for example, use of conceptual questions such as the graphic representation of gaseous equilibrium in Collins' test (Appendix E), or questions that required qualitative inferences or problem solving. An example included on Henry's test, question 9, required no calculation, but asked that students substitute

algebraic values correctly in an equilibrium expression. Henry explained that questions of this type tested students' ability to use qualitative thinking to guide a mathematical solution.

Both teachers used classroom questions and answers to engage students' thinking as a way of assessing their ability to reason qualitatively in explanation and problem solving. Examples are seen in Henry's question and answer session on equilibrium problems and Collins' interactive problem solving. Finally, both teachers also used homework assignments as a way of checking students' conceptual and procedural knowledge.

These forms of assessment simply did not exist in the traditional courses. Both conceptual teachers indicated that their instructional decisions were ultimately influenced by the knowledge of student performance gained from these individual and group methods. The feedback students received because of the conceptual assessment methods may also have served to promote their progress toward conceptual understanding.

Individual Results

The student interviews serve as a link between teachers' classroom practices and student learning. Out of twenty-one students who were either formally or informally interviewed, eight students participated in all phases. The information that follows is a summary of their responses. I am not proposing that generalizations about whole classes of students can be made from so small a sample. I am suggesting that the interviews help fulfill a need to gain some sense of the individual student's perspective on the courses. These perspectives in turn helped inform my analysis of class-level effects of traditional and conceptual teaching.

Traditional Students

Michelle was a pre-med student who had taken the Chem 1201 prerequisite under Reed where she received a course grade of A. At the time of her interview, she was also making an A in Chem 1202 and the course appeared to have met her expectations in most respects. Her only negative comment concerned an organizational aspect, the volume of material that Reed expected his students to cover. Michelle believed that she would have benefited from a more in-depth exposure to the course content than she had received.

CK: You mentioned that there is a problem with the amount of material?

Michelle: I would like it if he went a little slower... and not try to finish the whole book. It's more important to understand than to cover everything.

Gary was a transfer student from LSU-Shreveport where, as a freshman, he had taken the equivalent of Chemistry 1201. During his first semester at LSU - BR, Gary had enrolled in Chemistry 1202 under Reed. However, within a few weeks, he decided to drop the course.

Gary: It was just too difficult, particularly with the academic load I was carrying.

At the time of his interview he was carrying fewer hours than he had the previous semester and thought he might earn a grade of B. When I asked how he felt about the way the course was being taught, his response was surprising.

Gary: I took it last semester before I dropped it, and, ah, he's changed the way he teaches it. I don't know what he did over the summer but his approach has changed.

CK: How did it change?

Gary: He explains a lot more. Before, he was difficult to follow in his explanation and mostly it was problem solving. Now he's even asked for suggestions about how to improve the course. He didn't do that last time. He just went on through. If you understood, great. If you didn't, well you just read the book.

CK: Can you tell me a little more about his change in teaching?

Gary: Well, it's just more explanation now. Before he talked about experiments and it was just all problem solving. I didn't have a good background in chemistry, so I needed more time to understand it...you know, draw a little more and explain more details.

Neither Michelle nor Gary commented on Reed's assessment practices except to note that they were fair. However, Gary's comments on a change in his instruction supported what I had already begun to suspect based on the teacher interviews. Reed's conception of teaching was itself in the process of conceptual change.

Scott was a zoology major with a strong, general interest in science. He had been an honor student in high school in the college preparatory curriculum and had a small scholarship to attend LSU. Scott was disappointed in his performance in Hoffman's course. His concern was not strictly related to his course grade which was a C, but to his belief that neither he nor anyone else had learned much chemistry. In Scott's opinion, students who had done better in Hoffman's class either had high math aptitudes or were simply test-smart and could anticipate what would be on Hoffman's tests. Scott went into some detail explaining this.

CK: The problem with the course as you described it was that the teacher didn't explain enough. Was it too theoretical?

S: Umm. He wasn't theoretical at all.

CK: Oh?

- S: He was strict, if anything, he was strict numbers, strictly problem solving. No the thing I didn't get out of the course was theory.
- CK: O.K.
- S: ...because that is something I can usually pick up pretty fast.
- CK: O.K., so what did you do to prepare for tests?
- S: Well, I studied the text and I worked with several students. We all studied in the chemistry library.
- CK: How about help sessions after class?
- S: We went to them initially. Especially in the computer lab, but I think it was counterproductive.
- CK: Why is that?
- S: When I talked to him (instructor) he wanted me to use the computer but the problems in the book that he suggested to us weren't really on the same level as the questions of the test even though they came from the book. They were much more difficult, I thought. I never knew what to expect from him.
- CK: How did you do in the course?
- S: I got a C. A high C. I thought I was going to receive a B. Actually those who got a C thought they were doing pretty good, especially when you have about 100 to start and only 25 to finish.
- CK: What changes in the course would have helped you personally?
- S: I would have liked to have seen him discuss more theory, because I thought it was going to be more a theoretical course than it turned out to be. It was very quantitative. I think as important as the problem solving was, he just never tested us on the material that I think was.... I know everyone else learned the material that was important to know, but we weren't tested on it.
- CK: Uh hum.
- S: So, some of us got the impression that it wasn't important to know, He tested on problem solving. Those that were good at it did O.K.. They seemed to know what kind of problems to expect on the tests. I still don't think they learned the theory as much.

Richard, like Scott, was neither satisfied with Hoffman's teaching or his own performance.

Richard: He made it clear that if you didn't learn it you were going to fail. He made it clear that if you weren't serious enough about it, you're not going to learn it. Well, I took it real seriously and I still had a lot of trouble with it, and I didn't get any help. I think he hurt a lot of grade point averages by that, but I think a lot of people thought they would just have to try harder. A lot of others just gave up and dropped anyway.

Conceptual Students

David was majoring in chemical engineering. I interviewed him within a few days of the final examination in Henry's class. Although he had a positive attitude about the course and Henry's teaching methods, he felt that he had not made the effort he should have because of the heavy class load he had carried during the semester.

D: I mean I think the way he did the course is a great way to do it. It's so much more interesting..most classes really sit there and fall asleep..especially in a big room like that. But it was very interactive. He had everybody in a group, and called on people. He kept them stimulated to learn, at least, and the fact that he was flamboyant and excited about what he was doing. I have found in the past, and I, I can't really keep up with it because of the load of work, that I do better when I write things.

CK: Um hum.

D: And the fact that all his notes were already done - I don't remember things as well if I read them than if I write them.

CK: That's an interesting point.

D: But he did lay out the notes real well. And it helps keep you with a good attitude

CK: Did you use the text at all?

D: Off and on...but I believe I could have done the whole course without the text. I kept going back to the textbook looking up information because it's pretty authoritative.

CK: You felt you had a time problem?

D: No doubt, I had a calculus class that was killing me...and I was carrying 17 hours altogether. I have to admit I didn't do a lot of the work on homework because I was swamped. We'd get together and some of us would have all the work done and some of us had more of it...and we'd kinda go over it. I don't think the group work made me think that much just because I could rely on other people as my group and I know I had a safety net - you could drop a test you know, and do extra work.

Derek, who was majoring in anthropology, also took Henry's class. However, unlike David, he relied more on the class notes which he felt focused on the important concepts. His comments at the end of the interview were particularly interesting.

Derek: I'm surprised I remembered all that stuff.

CK: What do you think helped?

Derek: Well, he always did a few things in class instead of just lecture. Like his demonstrations. He did one with equilibrium where he used water in two containers and lifted one up and then switched sides and it went back and forth. That's what he used for equilibrium and Le Chatelier's principle.

CK: Did that help you remember the concepts?

D: Well, it helped you remember that if you affected one side by adding products or reactants it's going to flow to the other side. I know its basic, but for some people it's hard to see it without something like that.

Grace was an older, married student who had attended college intermittently. Her career choice was nursing. She didn't regard herself as particularly strong student in science and math and she found chemistry to be especially difficult. However, Grace was persistent and she appreciated Collins' visual approach to instruction to help students grasp otherwise obscure and abstract concepts. Problem solving presented the greatest difficulty and because she thought it required more skill than she believed

she could acquire, she had considered dropping the class. However, at the time of the last interview she was maintaining a C average and hoped to complete the course. She thought Collins' weekly tests were very fair.

Frank, a psychology major, was also enthusiastic about Collins' approach to teaching chemistry including the course's organization, instruction and testing. He was able to follow her classroom presentations closely using the notes and could understand her explicit problem solutions. He commented that the interactive format was especially good in helping him understand his mistakes. Frank was obviously enjoying the course and he had a good understanding of the material. I suspect he could have successfully switched his major into chemistry if he had desired.

Individual Results: Equilibrium

Chemical Equilibrium also served as a topic to investigate some individual aspects of student classroom learning. This portion of the study focused on students' understanding of equilibrium concepts and their ability to apply them in problem solving .

Understanding can be described as a function of the number of elements of knowledge that an individual possesses about a concept, the mixture of different types of elements and the pattern of associations perceived among them. From this perspective, a concept can be considered as the total set of knowledge that an individual associates with a label (i.e., propositions, images and skills). The cognitive objective of the student interview was to evaluate this multidimensional aspect of student knowledge as it related to the topic of chemical equilibrium.

If it is assumed that the meaning of a concept consists of its relationship with other concepts, then the conceptual structure of knowledgeable students should demonstrate more concepts and more relationships. Theoretically the better concepts are organized and integrated into such a structure, the easier they can be stored and retrieved from memory. In the first part of the interview, uncued recall techniques were used to identify the concepts that students could access from memory. (This process was assisted by the researcher who recorded the information on cards to be analyzed later in a concept map. See methods section). Only the concepts introduced by the students were utilized. To determine the extent of their propositional knowledge, students were required to explain their understanding of the concepts in response to free definition questions. This resulted in a set of student generated propositions. Students were then asked to construct a concept map that best represented their understanding of the relationships among the concepts.

One of the differences between the two groups of students occurred in their responses dealing with their knowledge concerning key theoretical concepts. The average number of concepts and propositions was greater for the conceptual students compared to the traditional students. The traditional students also displayed a greater frequency of missing concepts and these were generally at a higher level of abstraction. For example, Le Chatelier's principle was not recalled as a qualitative, theoretical concept by either of Hoffman's students, but was identified by all of the conceptual students in both their concept maps and problem analysis. The form of knowledge was also a factor. A review of both the transcripts and concept

maps indicated a differential focus on mathematical concepts and formulas as organizing elements. This was possibly the most obvious difference in the concept maps. The four traditional students organized their maps around mathematical equations and the equilibrium constant or omitted qualitative concepts such as Le Chatelier's principle. Good examples are provided on Michelle's and Scott's maps (Appendix O). This suggests, as Wilson (1992) noted, that these students perceived the mathematical relationship between the equilibrium constant and the concentration of reactants and products as a central organizing construct in chemical equilibrium theory.

The capacity to represent a concept in memory is fundamental to understanding. However, as Reif (1981) observed, student knowledge may be recalled and verbalized but not applied. The knowledge remains nominal, rather than functional, as the student can recall propositions but cannot otherwise apply a concept. The second part of the interview was designed to assess this aspect of understanding in problem solving applications. However, there is a second consideration. A problem solution does not necessarily guarantee that appropriate concepts and propositions have been invoked. As noted earlier, students can use algorithmic strategies to produce right answers to chemistry problems without much understanding of the chemistry involved.

The first problem was designed to address these issues. It had no mathematical content. However, this problem required a conceptual understanding of the molecular chemistry involved. While an algorithm would not solve the first problem, the second was a fairly conventional

textbook problem that it was possible to solve by algorithm (problems appear in Appendix F).

Results of problem solving indicated that traditional and conceptual students might have used similar procedures, yet differed in the knowledge possessed and applied. This seemed to indicate at least two levels of understanding. While lack of chemical understanding did not limit solving the traditional problem, it did preclude solution of the conceptual problem which required a nonalgorithmic and qualitative interpretation of Le Chatelier's principle. For example, although several students could recall Le Chatelier's principle and state it in propositional form they could not apply it to solve the conceptual problem. The most obvious example of this was Michelle. Michelle may have been the most skilled problem solver of the students I interviewed. Yet, even though she could describe Le Chatelier's principle and included it in her concept map, she could not recognize an application of it in the qualitative context of the conceptual problems. Gary, likewise, could state Le Chatelier's principle, but he could not interpret the conceptual problem by applying it. In the case of Hoffman's students Scott and Richard, the concept was neither recalled from memory nor recognized in problem solving. I concluded that as a theoretical concept, Le Chatelier's principle was not nominally or functionally present in their understanding of chemical equilibrium. This is indicated by Scott's response to my questioning.

S: I know its an underlying principle, but I don't recall as much as that he went over it. He was just expecting us to know...but I think he took it all the way through (the course) without mentioning it...but it shows up again, doesn't it?

Actually, Hoffman mentioned Le Chatelier's principle once, in the context of solving a quantitative problem.

Table 8
Results of student interviews on equilibrium

Traditional Students	Concepts	Propositions	Misconceptions	Problem Solving	
				Conceptual	Traditional
Michelle	14	14	-	x	✓
Gary	11	9	2	x	✓
Scott	11	10	-	x	✓
Richard	8	10	1	x	x
Conceptual Students					
David	12	14	1	x	✓
Derek	14	15	-	✓	✓
Grace	10	7	1	x	x
Frank	12	12	-	✓	x

The results of the interviews are summarized in Table 8. The check marks under problem solving indicate a correct response, while the x's indicate incorrect responses. Individual concept maps are included in the appendices. The first eight were constructed by the students. The last two were constructed by conceptual and traditional teachers, respectively.

Class-level Results

Class-level performance was compared on attrition, attitudes, and conceptual and quantitative portions of final examinations and tests.

Attrition

Table 9 presents the percent of attrition from the study classes based on department enrollment records covering the period from Spring, 1992 to Fall, 1994. The conceptual classes enjoyed comparatively lower attrition

rates when matched to traditional classes on a semester-by-semester basis. The overall department attrition outside the study classes was around 20%. Prior to the study, Reed's attrition was 17.8% of his classes, somewhat closer to the department average.

Table 9
Course attrition as percent of enrollment

Course	Spring 1992	Fall 1992	Spring 1993	Fall 1993	Spring 1994	Fall 1994
Hoffman	-	-	68.0	-	71.8	-
Reed	17.8	12.8	16.6	1.5	13.8	12.7
Henry	-	0	-	0	-	8.0
Collins	-	-	15.7	-	-	-

Attitudes

Table 10 presents attitude test results for conceptual and traditional classes over the course of this study (See Appendix G for questionnaire).

As the scores indicate, students who completed the conceptual courses were decidedly more positive about their experience than their counterparts in the traditional courses.

Table 10
Attitude score by class

Course	Number	1992	1993	1994
Conceptual	195	79.9	72.2	77.3
Traditional	118	69.8	65.9	54.2

If a primary objective of conceptual chemistry was to help students achieve a basic understanding of chemistry concepts (Item 2), the classes were successful as far as the students were concerned. Students agreed overwhelmingly that Henry's (96.7%) and Collins' (77.8%) courses had achieved that objective. This compares with about a third (36.8%) and half

of Reed's students (53.9%) who were in agreement with the statement. Item 5 addressed the issue of content organization. More students agreed that Henry's (70%) and Collins' (79%) courses taught them how important concepts were related to one another. Fewer students agreed that Hoffman's (31%) or Reed's (53%) traditional organization had helped them understand the relationships among concepts. A higher percentage of students also felt that their problem solving skills (Item 19) were improved by the conceptual teaching methods employed by Henry (81.7%) and Collins (75%) compared with Hoffman's (52.7%) and Reed's (64.1%) students. Class notes and teacher presentations (Item 12) were identified as a most important contributor to learning in Henry's (98.3%) and Collins' courses (69.8%). This compared with only 26.3% in Hoffman's class. Some 42.1% of his students were undecided on this item.

A larger proportion of traditional students believed they had learned chemistry primarily from the textbook (Item 8, Reed, 43.5%) and Hoffman, 47.4%, compared to conceptual students (Henry 28.6% and Collins 33.2%).

Homework assignments (Item 18) were also seen as a positive factor in learning in Henry's (93.3%) and Collins' classes (80.9%), whereas 42.1% of Hoffman's and 41.1% of Reed's students agreed that homework helped them learn chemistry.

Attitudes concerning what may be referred to as fairness issues also differed greatly between traditional and conceptual students. Nearly half (47.3%) of Hoffman's class and 38.5% of Reed's indicated that the course was designed to weed out the unfit (Item 10). Only 20% of Henry's and 25.3% of Collins' students agreed with this assessment. As suggested by

student interviews, the fairness of the tests administered by Hoffman was an important factor in his students' negative attitudes. Only 21% of his students would agree that his exams were fair (Item 3). The student interviews suggest that students felt they frequently were tested on material that they hadn't studied.

Closely related to this issue is the belief that it is possible to make a decent grade with reasonable effort (Item 4). The majority (96.6%, Henry and 96.8%, Collins) felt they could. The majority of Reed's students (76.9%) also agreed while the majority of Hoffman's students (52.7%) disagreed that there was a reasonable chance of a decent grade, even with effort. This class-level attitude result closely paralleled the remarks of Hoffman's students in the interviews and is probably also associated with the high attrition from his classes.

The traditional students also felt that adequate learning resources were not available to them outside of the class, the computer labs and teaching assistants notwithstanding (Item 6). This was particularly true among Hoffman's students, who presumably felt the need for such assistance. Only 4.6% would agree that enough help was made available to them. This compared with a third of Reed's class (33.4%) and 83.3% and 68.2% for Henry's and Collins' respectively, who agreed.

The majority of Hoffman's students agreed with the equivalency of problem solving with conceptual understanding in chemistry (Item 16) (Hoffman, 86.1%), while only 20.% of Henry's students agreed with the statement that problem solving and conceptual understanding were equivalent. This result may reflect the relative emphasis given to problem

solving in teaching and testing in Hoffman's classes. Table 11 summarizes the item analysis.

Table 11
Item Analysis

Item	Traditional	Conceptual
1. Course was enjoyable	32.7	64
2. Teacher explanations helped in understanding concepts	40	87.3
3. Exams were fair	51.6	77.9
4. With effort, everyone had chance for good grade	54.3	96.7
5. Course helped show the relationships among concepts	42.7	74.7
6. Enough help outside classroom	18.9	45
7. Course was difficult	82.1	59.6
8. Textbook was most important in learning concepts	45.5	30.9
9. Atmosphere was competitive rather than cooperative	47.3	21.4
10. Course designed to weed out unfit	42.7	22.7
11. Too much emphasis on problem solving and not enough on concept learning	52.2	23.3
12. Lecture and class notes most important in learning content.	32.5	84
13. Don't want any more courses like this one	58.2	24.8
14. Course will motivate students to become chemistry major	31	70.5
15. Interested in taking more courses like this one	22	54.9
16. Quantative problem solving is best test of conceptual understanding	55.9	32.2
17. Course shows importance of chemistry to everyday life	68.7	85.4
18. Homework assignments were most important in learning content	41.6	87.1
19. Course helped in understanding problem solving	58.4	78.4
20 Like chemistry more after course	35.8	59.3

Chemistry Test

The researcher-designed chemistry test was administered to Hoffman's and Henry's classes to compare their conceptual and quantitative knowledge (see Appendix F for test).

Table 12
Comparison of chemistry test scores

Class	N	Post T	Post C	Post Q
Traditional	14	27.249	10.714	16.535
Conceptual	38	28.571	13.214	15.357

Table 12 is the initial comparison of group means on the chemistry post test which show conceptual students apparently outperforming the traditional students on the posttest and conceptual subtest. An analysis of covariance was then used to compare total posttest scores using the pretest scores as a covariate. This analysis was followed by separate ANCOVAS for the quantitative and conceptual subtests. Results of the analysis indicate no significant differences between group means ($P < .05$). The ANCOVA source tables for each test are included as Appendix N.

Final Examination Performance

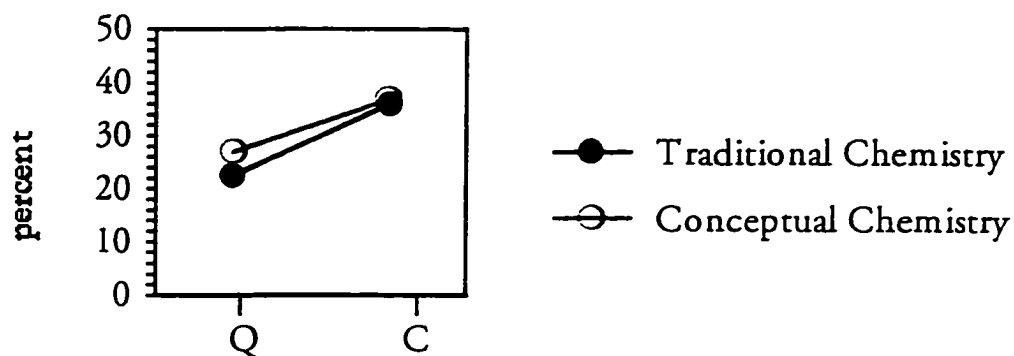
The line graphs on page 108 are calculations of mean percentages of correct answers on conceptual and quantitative portions of the department final examinations. The final examination was made up each semester by the teachers who had taught 1202 during that semester. Consequently, the examination questions differed from semester to semester although the same content areas were tested. The results are based on the item analyses of the tests from three semesters (included as Appendix L).

Table 13 includes the final examination scores for six sections of chemistry 1202 from 1993, the only time this information was available. In this case, the percent attrition has been calculated for each section and included for comparison.

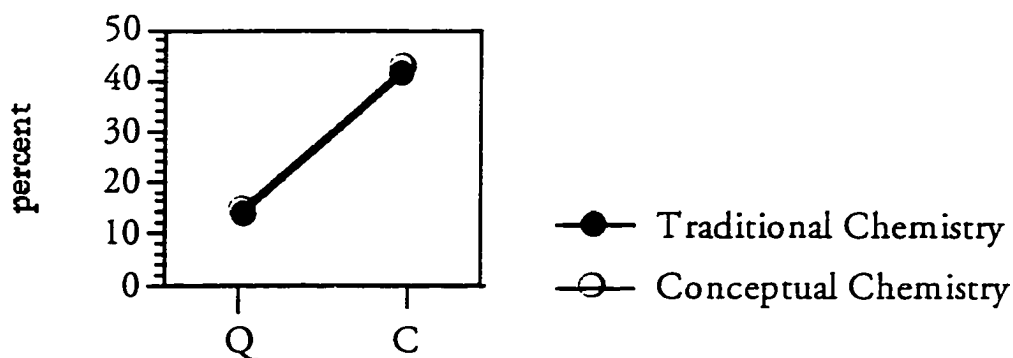
Table 13
Class average final exam score (1993)

Section	Instructor	Class average final exam score	Percent attrition
1	Collins	63.47	15.7
2	Taylor	60.19	17.8
3	Wallace	53.7	29.3
4	Reed	59.82	11.3
5	Reed	63.42	21.9
6	Hoffman	56.48	68.0

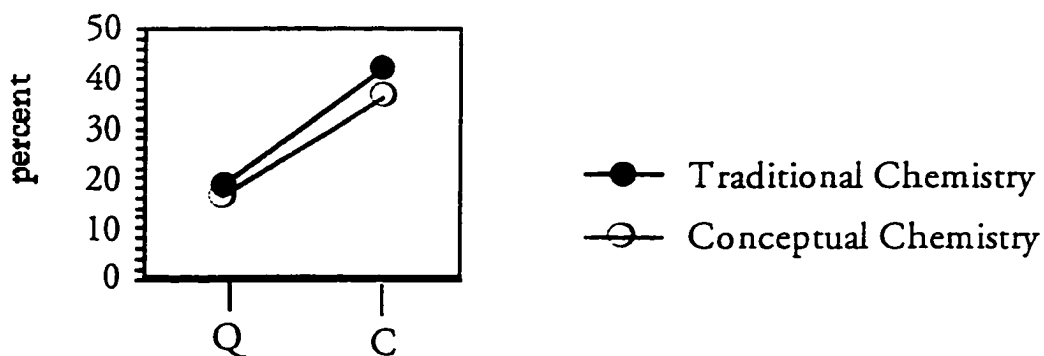
The class-level advantage offered by comparatively high test scores and comparatively low attrition in Collins' conceptual class is obvious when compared with the other sections. Compared with Hoffman's section, the differences are dramatic. Presumably courses like Hoffman's would select only those students with demonstrated problem solving skills and general proficiency in chemistry. In short, the top-tier students. During the interviews, I detected a kind of perverse pride in one of Hoffman's students who suggested that the survivors of his course could outperform any other sections on the final. As these results demonstrate, neither Hoffman's nor Reed's courses conferred a measurable advantage to their students in performance on standardized tests when compared with conceptual classes. When other factors such as attrition or attitudes are considered along with test scores, conceptual students are seen to hold a distinct group advantage compared to traditional students. Table 14 shows composite scores.



Mean percentage of correct answers on questions testing quantitative (Q) and conceptual (C) knowledge for two different classes (1992)



Mean percentage of correct answers on questions testing quantitative (Q) and conceptual (C) knowledge for two different classes (1993)



Mean percentage of correct answers on questions testing quantitative (Q) and conceptual (C) knowledge for two different classes (1994)

Figure 4
Percentage of correct answers by class on conceptual and quantitative portions of final exam

Table 14
Composite values for traditional and conceptual classes

	percent attrition	attitude score	chemistry test score	final exam score
Traditional Students	26.9	63.3	27.2	57.7
Conceptual Students	5.9	76.5	28.6	58.2

Students in the conceptual classes suffered considerably less attrition, enjoyed more positive attitudes and performed at least as well on conventional and research-based tests of concept learning and problem solving. Preliminary evidence from individual concept map construction and propositional analysis also suggests that conceptual students may have had a better grasp of qualitative, theoretical concepts and relied less on algorithmic problem solving. However, due to the small sample size, analysis of the results of individual student testing remain tentative and cannot serve as the basis for generalizations concerning whole classes of students.

CHAPTER 5
CONCLUSIONS
Teacher Conceptions
Student Learning

Hoffman's traditionalism was expressed by his insistence on a linear organization of topics, his almost exclusive use of the expository lecture, his deductive explanations and problem solving and his quantitative and evaluative approach to assessment. An interpretation of Reed's conceptions were more problematic. At times his assumptions about teaching chemistry included a hybridization of learning theories. For example, his insights into student thinking and the role of analogical thought processes suggest constructivist influences. In a sense, his insights into his own teaching may have defined a subtle but important distinction between behaviorist and cognitive learning theory, as applied to teaching. This occurred when he contrasted his use of analogies with the use of German mathematical logic (see comments on page 59). However, in practice, Reed used verbal analogies only occasionally in the context of his deductive explanations or mathematical problem solving. In addition, neither he nor Hoffman were observed to plan for or directly address student misconceptions as impediments to learning during classes. Nevertheless, Reed's expressions of concern about his teaching practices may represent some weakening of his earlier commitments to didactic teaching and a rational concession to some aspects of constructivist theory. He was certainly less of a traditionalist than Hoffman. He was also less of a constructivist than either Collins or Henry. In the final analysis, didactic and constructivist forms of teaching must

represent not a dichotomy, but different points on a continuum of teaching conceptions and characteristics.

Both Henry and Collins held views of chemistry teaching and learning that were consistent with constructivist theory. Their instruction emphasized the interrelatedness of concepts and the interaction of students' cognitive structures with new knowledge, either with course content or the cognitive structure of others. From a constructivist perspective, their teaching was an attempt to help students construct mental representations of chemistry's theoretical concepts and processes through analogical reasoning which featured physical and molecular models. This generally followed a two-step process. The first involved qualitative reasoning to promote acquisition of the target concept, while the second step involved concept applications in qualitative prediction, explanation, and in quantitative problem solutions. Their course objectives were clear: students must build up a repertoire of thoroughly understood and usable concepts, theories and techniques and demonstrate their understanding in contexts other than standard tests of problem solving. Thus, student knowledge and thinking were taken into consideration in planning and instruction to an extent unknown in traditional classes. Henry's and Collins' approaches were very similar in this regard. One of the few observed differences between them during actual classroom instruction was Henry's emphasis on small group interactions compared with Collins' whole class instructional approach.

Unlike traditional multiple choice testing, constructivist assessment methods are not standardized in conventional formats. Consequently,

there was more variability between Henry and Collins in their conceptions of assessment. Henry preferred multiple formats including tests, essay writing or interactive questions and answers. Collins utilized frequent testing with an equal mix of conceptual and quantitative problems and interactive problem solving.

Content Knowledge

Traditional conceptions of content knowledge are understood to partly result from the growth of a particular kind of mathematical modeling of chemical phenomena. At its center was an assembly of deductive models tightly bound to the empirical data they explained. For many traditionalists these formal models represent the network of received truths by which the science is currently defined. Lacking a truly cognitive perspective of knowledge acquisition, the traditional teachers emphasized the logical presentation of this knowledge on the part of the teacher and the role of attention and effort on the part of the student.

By contrast, the epistemic assumptions of the conceptual teachers required that they find close correspondence between ideas that made chemistry intelligible to the chemist and ideas that made chemistry intelligible to the student. This, in effect, required that they had the ability to relate their own content knowledge to their students' understandings of chemistry knowledge. This conception of teaching departs substantially from traditional practice and frames an active role for students as constructors of knowledge and teachers as co-constructors. The way this was demonstrated was through the construction of nonformal or qualitative methods of representing chemistry to complement its formal

representation. One of the most resilient findings concerning the genesis of scientific knowledge is that these qualitative aspects are a necessary foundation for mathematical understandings. Scientists might mathematically symbolize their understanding of a concept or principle, but these are believed to play only a small role. The symbols and formulas of formal science connect to richly elaborated conceptual and procedural constructs which function in logical reasoning and problem solving (di Sessa, 1987). Rather than relying solely on deductive analysis, the conceptual teachers employed a variety of qualitatively different models to represent the theoretical concepts and processes embedded in the empirical data, and in the mathematical formulas and equations of the text. For example, dynamic equilibrium was represented as a visually explicit molecular model instead of a kinetic profile. The equilibrium constant, which informs about the changes in the relative concentrations or volumes of reactants and products through mole ratios, was visually and verbally expanded to include the notion that mathematical ratios of product and reactants can be understood as ratios of molecules. In addition to calculating the reactant quotient to algorithmically predict the direction of equilibrium shifts, conceptual teachers' explanations also employed models to teach students to qualitatively decide how an equilibrium system would shift in response to various parameters, and how to translate the qualitative understandings into mathematical equations (see Appendix D).

Implications

Changes in teachers' conceptions of science knowledge and its acquisition have profound implications for student learning and the

reform of science teaching generally. If learning occurs as constructivist theories purport, particularly learning of abstract and theoretical content, then teaching involves far more than the dissemination of correct scientific knowledge. The fundamental pedagogical objective becomes a search for ways to engage students in learning to achieve understanding. This requires an awareness that student interpretations depend upon the availability of appropriate mental structures for concept learning and problem solving.

Research has shown that students often begin their studies with misconceptions about the content they're studying and that remnants of these may persist even in students who receive high grades in their courses. These errors are often not simply careless mistakes or the results of flawed reasoning. They may in fact represent what students believe is reasonable given their current knowledge structure or prior knowledge. An awareness of these psychological factors can provide teachers with insights into the type of content organization, instruction and assessment that has the best chance of success. What these concerns mean is that the teacher's role is different from one frequently envisioned in traditional conceptions of science teaching. What has changed is the realization that science teaching is not only the ability to articulate a large number of relevant facts or engage in deductive analysis. Teachers must also have the capacity to get students actively engaged in learning. This involves the pedagogical knowledge that can guide the selection of and organization of appropriate content, an awareness of cognitive processes that must be used to learn the content and an understanding of how existing knowledge structures

determine what and if students learn from the content presented. Constructivist conceptions of teaching require that teachers know more about the ways in which specific content and instructional practices engage or elicit the psychological processes and knowledge structures appropriate for the objective of conceptual understanding. In conceptual chemistry this had to do with explicit instruction to enhance students' capacity to abstract the concepts from different contexts, whether embedded in pictures, manipulative models, demonstrations, spoken language or mathematical symbols, and to reason qualitatively with these as theoretical constructs in explanations and problem solving.

Pre-service Education

Most of the literature on teacher knowledge indicates that there exist at least two knowledge structures: content and pedagogic. Work by Hauslein, Good and Cummins (1992) suggests that at some point in their pre-service training or upon choosing teaching as a career, a teacher's content knowledge becomes fixed upon the pedagogic structure. When they are taught content, many pre-service teachers may not be sufficiently motivated to construct an idiosyncratic meaning for the content (i.e., establish a meaningful cognitive structure). Upon entering professional service as teachers, content knowledge is simply subsumed into what works pedagogically within the curriculum. I suggest that this process may very well describe the origins of didactic teaching. The implications of this model for teacher education is in support of the need for teachers to construct meaningful conceptions of both content and pedagogy; simply requiring more science content is obviously not the answer.

Ideally, pre-service teachers would experience constructivist forms of science teaching that would be congruent with what they expect to teach in the future. In this way they would gain experience with both a form of pedagogy and content that is at once recognizable, but clearly distinguishable from traditional forms. The current state of science education suggests, however, that this ideal is not easily obtained. In the interim, the responsibilities for engineering the reform of science teaching will likely fall upon the colleges of education through pre-science teacher preparation. This is indeed the rationale for Stofflett's (1994) proposal to apply conceptual change theory to help pre-service teachers reconstruct their content and pedagogical conceptions.

When teachers enter the classroom to teach, they bring with them their conceptions of the content to be learned and the pedagogy for teaching it. These pedagogical conceptions are thought to form a kind of cognitive filter through which new information is processed and understood. If teachers' conceptions tend to be didactic, then their teaching practices will tend to be didactic. The question for teacher education is how to adequately challenge teachers' prior conceptions of teaching. Constructivists would argue that developing new understandings requires an authentic experience that challenges their prior knowledge and epistemic assumptions.

Stofflett (1994), for example, suggested that by providing an example of conceptual change instruction, teachers will be challenged to incorporate the learning model into their conception of teaching. Teaching activities would then be suggested that would take into account

students' concepts. One problem with this approach is that it focuses too narrowly on instruction. The conceptual change model as a teaching model does not speak to the issue of how student conceptions can be taken into account in curriculum organization nor in assessment practices. Yet these areas are essential if teachers are to construct a coherent conception of science pedagogy. The low rate of use of conceptual change teaching strategies may be attributable in part to the fact that the task of curriculum reconstruction alone is formidably difficult for most teachers (Hollon, Roth and Anderson, 1991). Smith, Blakeslee, and Anderson (1993) noted that teachers using commercial materials can teach for conceptual change only by engaging in a difficult, complex and time consuming process of curriculum reconstruction.

Future Research

This study has demonstrated that constructivist forms of teaching are possible, even in large, entry level college courses. Conceptual chemistry demonstrates, if nothing else, that it is possible to design a college level science curriculum with the objective of promoting in-depth and personal understanding of science concepts and processes for the majority of students. Some constructivists may question the notion that the instructional methods used by Henry and Collins could elicit conceptual change. However, it is reasonable to assume that their use of analogies and real world examples highlighted the understandings and usefulness of the target theoretical concepts. The intensive question and answer sessions and interactive problem solving exercises generated the conceptual conflict specified by Posner's *et al.* (1982) model. The key point is that their

constructivist approaches were designed to challenge preconceptions and restructure knowledge, precisely the objectives of conceptual change teaching. Further research will be required to disentangle the effects of specific instructional variables (e.g., the use of graphics, demonstrations or questions and answer sessions) but the success of their general method has been demonstrated.

Assessment practices in the conceptual classes were consistent with constructivist approaches to learning in that they allowed students to express their understandings in different ways rather than by relying exclusively on conventional short answer test questions. Research into this area is just beginning, but the early results are encouraging. Work by Pickering (1990), and Sawrey (1990), which expanded on the 1987 study of concept learning and problem solving by Nurrenbern and Pickering, has challenged traditional conceptions of learning and assessment in the physical sciences which have been axiomatic for decades. Research in this area suggests an avenue, in addition to conceptual change instruction, for influencing and changing teachers' didactic conceptions.

Other areas that offer potential research opportunities include the writing of science textbooks. Arguably, the translation of the private understandings of scientists into the public science of textbooks and science teaching should obtain a more adequate pedagogical representation. But as this and other studies have shown, representations of theoretical knowledge may be conditioned by underlying epistemological assumptions about the nature of knowledge and its acquisition. Thus, the assumptions of scientific empiricism and behavioral psychology have played a dominant

role in the traditional organization and representation of science content knowledge.

Some of the most recent work in science education draws on the findings of cognitive psychology which had established that there is frequently a substantial gap between what may be taught and how the student internalizes and then utilizes the information conveyed. Such insights into the psychological aspects of science learning argue for some organized form of internal representation that must be present to provide a framework for knowledge acquisition and use. This suggests that if conceptual understanding requires that students should attain a functional, as opposed to nominal understandings of concepts, then a pedagogical objective should be to emphasize different ways for students to first internally represent and then apply representations of the theoretical entities that are understood. In his discussion of science textbooks and science teaching, Arthur Stinner (1992) noted that,

The first widely used textbooks in elementary physics in the English-speaking world were written by William Whewell. In the preface of his *An Elementary Treatise on Dynamics* (1823), he especially compliments the continental mathematicians for their analytical skills in compressing the whole science into a few short formulae. In spite of this tribute, Whewell was deeply concerned about the seductive power of the finished product of mathematics in the teaching of physics. He argued that students should learn concepts outside the grip of a mathematical formulation. He thought that if they did not struggle through appropriate arguments based on intuition, space and geometry first, they would only 'learn to reason by means of symbols... and by means of the general rules of combining and operating upon such symbols, without thinking of anything but these rules' (Whewell, 1850).

Whewell put his pedagogical principle into practice by placing intuition, generic reasoning and pre-algorithmic discussion before the finished product of mathematical formulation. While it is arguable that textbooks in physics that followed were modeled after his, many of Whewell's pedagogical devices to explicate concepts prior to the presentation of the finished product were dropped. In these books, textbook authors first stated the principles, definitions and laws and then, sequencing the problems, asked students to work them out as an exercise. In contrast to Whewell's treatment, extensive discussion of the origin of and the evidential basis for mathematical formulations was discontinued. In the texts, example problems are worked out to illustrate the application of formulas only. It seems that post-Whewellian texts are the prototypes for today's physics and chemistry texts and they may have set the tone for the format of science texts in general.

Stinner (1992) notes that the teaching of science and the physical sciences has been a textbook-centered affair in the English-speaking world since Whewell's textbooks appeared in the 1820's. Science text writers as well as science teachers emphasize the finished product of scientific fact and the efficacy of applying the formulas in solving exercise problems (Hewitt, 1990).

Moreover, there is evidence to indicate that many students studying science see little connection between their ideas about the world and what they learn in science classes. Stinner (1992) suggested that what may lie at the heart of this problem is a sense of disconnectedness between the logic of the textbook and what counts as good reasons for believing. The

pedagogical question is how to link the real world with the abstract world of scientific concepts and processes. Whewell advocated the explication of concepts by appealing to students' experience and intuition prior to the final mathematical formulation. In doing so, he anticipated constructivist forms of pedagogy by more than one hundred years.

REFERENCES

- American Association for the Advancement of Science. (1989). Project 2061: Science for all Americans. Washington, D.C.: AAAS.
- Ausubel, D.P., Novak, J.D. and Hanesian, H. (1978). Educational psychology: A cognitive view. New York: Holt, Rinehart and Winston.
- Barnes, D. (1982). Practical curriculum study. London: Rutledge and Kegan Paul, Limited.
- Bogdan, R.C. and Biklen, S.K. (1982). Qualitative research for education. Boston: Allyn and Bacon.
- Brown, D.E. (1992). Using examples and analogies to remediate misconceptions in physics: Factors influencing conceptual change. Journal of Research in Science Teaching, 29 , 17-34.
- Bunce, D.M. (1996). The quiet revolution in science education - teaching science the way students learn. Journal of College Science Teaching, 25, 169-171.
- Camacho, M. and Good, R. (1989). Problem solving and chemical equilibrium: Successful versus unsuccessful performance. Journal of Research in Science Teaching, 26, 251-272.
- Clark, C.M. (1988). Asking the right questions about teacher preparation: Contributions of research on teacher thinking. Educational Researcher, 17 , 5-12.
- Clark, C.M. and Peterson, P.L. (1986). Teachers' thought processes. In M.C. Wittrock (Ed.) Handbook of research on teaching. Third edition. New York: Macmillan.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. Journal of Research in Science Teaching, 30 , 1241-1258.

- Cronin-Jones, L.L. (1991). Science teacher beliefs and their influence on curriculum implementation: Two case studies. Journal of Research in Science Teaching, 28, 235-250.
- diSessa, A.A. (1987). The third revolution in computers and education. Journal of Research in Science Teaching, 24, 343-367.
- Driver, R. (1989). Students' conceptions and the learning of science. International Journal of Science Education, 11, 481-490.
- Driver, R., Guesne, E., and Tiberghien, A. (Eds.) (1985). Children's ideas on science. Philadelphia: Open University Press.
- Duschl, R.A. and Gitomer, D.H. (1991). Epistemological perspectives on conceptual change: Implications for educational practices. Journal of Research in Science Teaching, 28, 839-858.
- Erickson, F. (1986). Qualitative methods in research on teaching. In M.C. Wittrock (Ed.) Handbook of research on teaching. Third edition. New York: Macmillan.
- Fishbein, M. and Ajzen, I. (1975). Belief, attitude, intention and behavior: An introduction to theory and research. Reading, MA: Addison-Wesley.
- Gallagher, J.J. (1991). Interpretative Research in Science Education. NARST Monograph, Number 4.
- Gold, M. (1988). Chemical education: An obsession with content. Journal of Chemical Education, 65, 780-781.
- Good, R.G. (1993). Editorial. Journal of Research in Science Teaching, 30, 1015.
- Gorodetsky, M. and Hoz, R. (1985). Changes in the group cognitive structure of some chemical equilibrium concepts following a university course in general chemistry. Science Education, 69, 185-199.
- Gowin, D.B. (1981). Educating. Ithaca, NY: Cornell University Press.

- Grandy, R.E. (1997). Constructivism and objectivity: Disentangling metaphysics from pedagogy. In Michael R. Matthews (Ed.) Science and education: Contributions from history, philosophy and sociology of science and education. Boston: Kluwer Publishers.
- Gregory, Eileen. (1992). Science literacy enhancement for nonscience majors - The Rollins College single term experiment. Journal of College Science Teaching, 21, 223-225.
- Gussarsky, E. and Gorodetsky, M. (1988). On the chemical equilibrium concept: Constrained word associations and conception. Journal of Research in Science Teaching, 25, 319-333.
- Hackling, M.W. and Garnett, P.J. (1985). Misconceptions of chemical equilibrium. European Journal of Science Education, 7, 205-214.
- Hashweh, M.Z. (1985). An exploratory study of teacher knowledge and teaching: The effects of science teachers' knowledge of subject matter and their conception of learning on their teaching. Dissertation, Stanford University.
- Hauslein, P.L., Good, R.G. and Cummins, C.L. (1992). Biology content cognitive structure: From science student to science teacher. Journal of Research in Science Teaching, 29, 939-964.
- Hazen, R.M. and Trefil, J.S. Achieving chemical literacy. Journal of Chemical Education, 68, 392-394.
- Heller, J.I., and Reif, F. (1984). Prescribing effective human problem-solving processes: Problem description in physics. Cognition and Instruction, 1, 177-216.
- Hewitt, N.M. and Seymour, E. (1991). Factors contributing to high attrition rates among science, mathematics and engineering undergraduate majors. Report by the Alfred P. Sloan Foundation. Bureau of Sociological Research. University of Colorado, Boulder, CO.
- Hewitt, P. G. (1990). Conceptually speaking. The Science Teacher, 54-57.

- Hewson, P.W. and Hewson, M.G. (1987). Science teachers' conceptions of teaching: Implications for teacher education. International Journal of Science Education, 9, 425-440.
- Holland, J.H., Holyoak, K.J., Nisbett, R. E., and Thagard, P.R. (1986). Induction: Process of inference, learning and discovery. Cambridge, MA: The MIT Press.
- Hollingsworth, S. (1980). Prior beliefs and cognitive changes in learning to teach. American Educational Research Journal, 26, 160-189.
- Hollon, R.E., Roth, K.J., and Anderson, C.W. (1991). Science teachers' conceptions of teaching and learning. In J. Brophy (Ed.) Advances in research on teaching Volume 2: Teachers subject matter knowledge. New York: JAI Press.
- Hoots, R.A. (1992). An outsiders' insights on neglected issues in science education. Journal of College Science Teaching, 21, 300-304.
- Hoz, R., Tomer, Y., and Tamir, P. (1990). The relations between disciplinary and pedagogical knowledge and the length of teaching experience of biology and geography teachers. Journal of Research in Science Teaching, 27, 973-985.
- Hutchinson, S.A. (1990). Education and grounded theory. In R.R. Sherman and R.B. Webb (Eds.) Qualitative research in education: Focus on methods. New York: The Falmer Press.
- Jick, T.D. (1979). Mixing qualitative and quantitative methods: Triangulation in action. Administrative Science Quarterly, 24, 600-611.
- Larkin, J. (1981). The cognition of learning physics. American Journal of Physics, 49, 534-541.
- Larkin, J. (1983). The role of problem representation in physics. In D. Gentner and A.L. Stevens (Eds.) Mental models. Hillsdale, NJ: Lawrence Erlbaum.

- Lawson, A.E. (1993). Deductive reasoning, brain maturation, and science concept acquisition: Are they linked? Journal of Research in Science Teaching, 30, 1027-1051.
- Lawson, A.E., Abraham, M.R. and Renner, J.W. (1989). A theory of instruction: Using the learning cycle to teach science concepts and thinking skills. Cincinnati, OH: National Association for Research in Science Teaching.
- Lawson, A.E., Baker, W.P. DiDonato, L., Verdi, M.P. and Johnson, M.A. (1993). The role of hypothetico-deductive reasoning and physical analogies of molecular interactions in conceptual change. Journal of Research in Science Teaching, 30, 1073-1085.
- Lederman, N.G., Gess-Newsome, J., and Latz, M. (1994). The nature and development of preservice science teachers' conceptions of subject matter and pedagogy. Journal of Research in Science Teaching, 31, 129-146.
- Leinhardt, G. (1983). Novice and expert knowledge of individual students' achievement. Educational Psychology, 18, 165-179.
- Leinhardt, G. and Greeno, J.G. (1986). The cognitive skill of teaching. Journal of Educational Psychology, 78, 75-95.
- Leinhardt, G. and Smith, D.A. (1985). Expertise in mathematics instruction: Subject matter knowledge. Journal of Educational Psychology, 77, 247-271.
- Marek, E.A., Eubanks, C. and Gallaher, T.H. (1990). Teachers' understanding and the use of the learning cycle. Journal of Research in Science Teaching, 27, 821-834.
- Maskill, R. and Cachapuz, A.F.C. (1989). Learning about the chemistry topic of equilibrium. The use of word association tests to detect developing conceptualizations. International Journal of Science Education, 11, 57-69.
- McLaughlin, M.W. and Talbert, J.E. (1993). Introduction: New visions of teaching. In David K. Cohen, Milbrey W. McLaughlin, and Joan E. Talbert (Eds.) Teaching for understanding: Challenges for policy and practice. San Francisco: Jossey-Bass, Inc.

- Morine-Dershimer, M. (1989). Prescience teachers' conceptions of content and pedagogy: Measuring growth in reflective, pedagogical decision-making. Journal of Teacher Education, 40, 46-62.
- National Science Foundation. (1987). Science and technology data book, 1988. Washington, D.C.: ERIC Documents.
- Navarra, J.G., Levin, J. and Navarra, Jr., J.G. (1992). Using an interactive database to develop a new paradigm. Journal of College Science Teaching, 22, 34-36.
- Nola, R. (1997). Constructivism in science and science education. In Michael R. Matthews (Ed.) Science and education: Contributions from history, philosophy and sociology of science and education. Boston: Kluwer Publishers.
- Nurrenbern, S.C., and Pickering, M. (1987) Concept Learning versus problem solving: Is there a difference? Journal of Chemical Education, 64, 508-510.
- Patton, M.Q. (1989). Qualitative evaluation methods. Beverly Hills, CA: Sage Publications.
- Pickering, M. (1990). Further studies on concept learning versus problem solving. Journal of Chemical Education, 67, 254-255.
- Pines, A.L., and West, L.H.T. (1986). Conceptual understanding and science learning: An interpretation of research within a sources-of-knowledge framework. Science Education, 70, 583-604.
- Posner, G.J. Strike, K.A., Hewson, P.W. and Gertzog, W.A. (1982). Accomodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.
- Reif, F. (1981). Teaching problem solving in a scientific approach. The Physics Teacher, 19, 310-316.
- Reif, F. (1987). Instructional design, cognition and technology: Applications to the teaching of scientific concepts. Journal of Research in Science Teaching, 24, 309-324.

- Reif, F. and Larkin, J.H. (1991). Cognition in scientific and everyday domains: Comparison and learning complications. Journal of Research in Science Teaching, 28, 733-760.
- Renner, J.W., Abraham, M.R., Grzybowski, E.B., and Marek, E.A. (1990). Understandings and misunderstandings of eight graders of four physics concepts found in textbooks. Journal of Research in Science Teaching, 27, 35-54.
- Rigden, J.S., and Tobias, S. (1991). Tune in, turn off, drop out: Why so many college students abandon science after the introductory courses. The Sciences, 31, 16-20.
- Rist, R.C. (1982). On the application of ethnographic inquiry to education: Procedures and possibilities. Journal of Research in Science Teaching, 19, 439-450.
- Roth, W.M., and Bowen, G. M. (1994). Mathematization of experience in a grade 8 open-inquiry environment: an introduction to the representational practices of science. Journal of Research in Science Teaching, 31, 293-318.
- Rummelhardt, D.E. and Norman, D.A. (1981). Analogical processes in learning. In J.R. Anderson (Ed.) Cognitive skills and their acquisition. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Saunders, W.L. (1992). The constructivist perspective: Implication and teaching strategies for science. School science and mathematics, 92, 136-141.
- Sawrey, B.A. (1990). Concept learning versus problem solving: Revisited. Journal of Chemical Education, 67, 253-254.
- Schibeci, R.A. (1984). Attitudes to science: An update. Studies in Science Education, 11, 26-49.
- Seidman, I.E. (1991). Interviewing as qualitative research. New York: Teachers College Press.

- Seymour, E. (1992). 'The problem iceberg' in science, mathematics, and engineering education: Student explanations for high attrition rates. Journal of College Science Teaching, 21, 230-237.
- Shepard, L.A. (1991). Psychometricians' beliefs about learning. Educational Researcher, 20, 2-16.
- Shulman, L.S. (1986). Paradigms and research programs in the study of teaching: A contemporary perspective. In M.C. Wittrock (Ed.) Handbook of research on teaching. Third edition. New York: Macmillan.
- Shulman, L.S. (1987). Knowledge and teaching: Foundations of the new reform. Harvard Educational Review, 57, 1-22.
- Shulman, L.S. and Tamir, P. (1973). Research on teaching in the natural sciences. In R.M.W. Travers (Ed). Second Handbook of Research on Teaching. Chicago: Rand McNally.
- Slavin, R.E. (1983). When does cooperative learning increase student achievement? Psychological Bulletin, 93, 429-445.
- Smith, E.L. and Anderson, C.W. (1984). Plants as producers: A case study of elementary science teaching. Journal of Research in Science Teaching, 21, 685-698.
- Smith, E.L., Blakeslee, T.D. and Anderson, C.W. (1993). Teaching strategies associated with conceptual change learning in science. Journal of Research in Science Teaching, 30, 111-126.
- Stinner, A. (1992). Science textbooks and science teaching: From logic to evidence. Science Education, 76, 1-16.
- Stoddart, T. (1991, April). Reconstructing teacher candidates' views of teaching and learning. Paper presented at the Annual Meeting of the American Educational Research Association, Chicago, IL.
- Stoddart, T. and Stofflett, R.T. (1992). Breaking the didactic teaching-learning-teaching cycle: Reconstructing teacher candidates' understanding of content

and pedagogy. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

- Stofflett, R. T. and Stoddart, T. (1994). The ability to understand and use conceptual change pedagogy as a function of prior content learning experience. Journal of Research in Science Teaching, 31, 31-52.
- Stofflett, R.T. (1994). The accommodation of science pedagogical knowledge: The application of conceptual change constructs to teacher education. Journal of Research in Science Teaching, 31, 787-810.
- Strike, K.A. and Posner, G.J. (1985). A conceptual change view of learning and understanding., In West, L.H.T. and Pines, A.L. (Eds.) Cognitive structure and conceptual change. New York: Academic Press.
- Tobias, S. (1990). They're not dumb, they're different: Stalking the second tier. Tuscon, AZ: Research Corporation.
- Toulmin, S. (1972). Human Understanding. Princeton, NJ: Princeton University Press.
- Vygotsky, L.S. (1978). Mind in Society. Cambridge, MA: Harvard University Press.
- Wandersee, J.H. and Abrams, E. (1994). Construction of concept maps in a clinical interview setting. Subject matter knowledge and conceptual change newsletter (AERA).
- West, L.H.T., and Pines, A.L. (1985). Cognitive structure and conceptual change. New York: Academic Press.
- Whewell, W. (1850). Of a liberal education. London: Parker Rare Books.
- White, R. and Gunstone, R. (1992). Probing understanding. New York: The Falmer Press.
- Wilson, J.M. (1994). Network representations of knowledge about chemical equilibrium: Variations with achievement. Journal of Research in Science Teaching, 31, 1133-1147.

APPENDIX A
PERIOD OF STUDY

Fall 1992	PILOT STUDY Preliminary classroom observations (Henry and Reed) Individual unstructured interviews Document analysis Development of research instruments Comparison of emerging themes
Spring 1993	MAIN STUDY Classroom observations (Collins) Individual structured interviews Class-level analysis of attitude survey and tests Analysis of enrollment data
Fall 1993	Classroom observations (Reed) Individual structured interviews Class-level analysis of attitude survey and tests Analysis of enrollment data
Spring 1994	Classroom observations (Hoffman) Individual structured interviews Class-level analysis of attitude survey and tests Chemistry pre-posttest Enrollment data
Fall 1994	Classroom observations (Henry) Individual structured interviews Class-level analysis of attitude survey and tests Chemistry pre-posttest Enrollment data

APPENDIX B
CHEMISTRY 1202 SYLLABUS

**Chemistry 1202 Syllabus
Revised, August 1992
McQuarrie and Rock**

- I. Liquids and Solids (Chapter 14, Secs. 1-4, 6, 7, 10)**
- A. Molecular characteristics of liquids and solids (Sec. 14-1). Molar volumes compared to that of gases.
 - B. Phase transformations (Secs. 14-2 and 14-3). Heating curve, heat of fusion and heat of vaporization, heat of sublimation. Carbon dioxide.
 - C. Attractive forces between particles (Sec. 14-4). Ionic, dipolar, and London forces, hydrogen bonding.
 - D. Equilibrium vapor pressure (Secs. 14-6 and 14-7). Dynamic equilibrium, vapor pressure curve, (normal) boiling point, relative humidity, dew point.
 - E. Crystals (Sec. 14-10). Atomic, ionic, molecular, covalent network, metallic. X-ray diffraction, graphite and diamond.
- II. Chemical Equilibrium (Chapter 17, all except Secs. 6 and 8)**
- A. Dynamic nature of chemical equilibrium (Sec. 17-1 and 17-2). Forward and reverse reactions.
 - B. Equilibrium constant expressions (Sec. 17-3 and 17-4). Form of expression, temperature dependence of K , units of K , partial pressures in equilibrium expressions, pure solids and liquids.
 - C. Calculating equilibrium conditions (Sec. 17-5).
 - D. LeChâtelier's Principle (Secs. 17-7 and 17-9). Equilibrium shifts caused by changes in concentrations, volume or pressure, or temperature.
 - E. Direction of reaction spontaneity (Sec. 17-10). Reaction quotient.
- III. The Ozone Hole (Interchapter H, all)**
- Ultraviolet radiation, chlorofluorocarbons (CFC's), freons, South Pole.
- IV. Acids and Bases (Chapter 18, all except Sec. 8)**
- A. Arrhenius and Bronsted-Lowry acids and bases (Sec. 18-1). Proton donors and acceptors, proton transfer reaction.
 - B. The ion-product of water (Sec. 18-2). Pure water, aqueous solutions.
 - C. Common strong acids and bases (Sec. 18-3).
 - D. pH of aqueous solutions (Sec. 18-5). Scale of pH, pOH, pH meter.
 - E. Weak acids and bases (Secs. 18-4 and 18-6). Carboxylic acids, carboxylate ions, ammonia.

- F. Equilibrium calculations with weak acids (Sec. 18-7). K_a .
 - G. Equilibrium calculations with weak bases (Sec. 18-9). K_b .
 - H. Conjugate acid-base pairs (Sec. 18-10). Relationship between strength of an acid and its conjugate base.
 - I. pH of aqueous solutions of salts (Sec. 18-11). Neutral anions and cations, basic anions, acidic anions, acidic cations
 - J. Lewis acids and bases (Sec. 18-12).
- V. Entropy and Chemical Reactivity (Chapter 22, Secs. 1-5, 7)
- A. Spontaneous processes (Sec. 22-1). Exothermic and endothermic reactions, energy-neutral processes (mixing of gases).
 - B. Entropy (Secs. 22-2 and 22-3). Irreversible processes, disorder.
 - C. Factors affecting entropy (secs. 22-4 and 22-5). Melting, vaporization, mass, molecular structure.
 - D. Energy-driven and entropy-driven reactions (Sec. 22-7).
- VI. Oxidation-Reduction Reactions (Chapter 21, Secs. 1-5)
- A. Oxidation states and half reactions (Secs. 21-1 through 21-3). Oxidation states from Lewis formulas, electron transfer, oxidation (reduction) half reactions.
 - B. Balancing oxidation-reduction reactions in aqueous solution (Secs. 21-4 and 21-5). Method of half reactions, acidic solutions, basic solutions.
- VII. Electrochemistry (Chapter 23, Secs. 1-5, 8-9, omit pp. 823-826)
- A. Electrical quantities (Sec. 23-1). Coulomb, ampere, volt.
 - B. Electrochemical cells (Pages 815 through 822.) Voltaic cell, salt bridge, anode, cathode, polarity of cell, types of electrodes, schematic cell diagram, qualitative effect of concentration on voltage.
 - C. Cell voltages from standard reduction potentials (Sec. 23-5).
 - D. Electrolysis (Sec. 23-8 and 23-9). Faraday's Law, the Faraday constant, chlor-alkali process, Hall process.
- VIII. Chemistry of the Main-Group Elements I (Chapter 25)
- A. Group 4 elements (Sec. 25-6, omit 25-6C, 25-6D, and 25-6E). Diamond and graphite, tin and lead.
- IX. Chemistry of the Main-Group Elements II (Chapter 26, Secs. 1, 2, 3)
- A. The nitrogen family (group 5 elements) (Sec. 26-1). Nitrogen fixation, Haber process, Ostwald process, Raschig synthesis, phosphorus.
 - B. The oxygen family (group 6 elements) (Sec. 26-2). Fractional distillation of air, photosynthesis, ozone, Frasch process, Claus process, sulfuric acid.
 - C. The halogens (Sec. 26-3). Important uses of compounds, chlorinated hydrocarbons, bromine and iodine, oxyacids of halogens.

APPENDIX C

Chemistry Instruction (Equilibrium)

Traditional

Reed: Let's take a cylinder - piston setup like this which contains liquid and vapor at equilibrium at some temperature and pressure. O.K., this is point A. Let's say we push the piston down. Well, we try to change the pressure to some other point (point B) which still has the same temperature as A, but is a higher pressure. We want to go up this line. What happens? The pressure doesn't increase. What occurs is that some vapor condenses into liquid. The pressure stays at the value A. We still have some vapor and liquid. You don't get to B until the piston is all the way down and the vapor condenses. Now if you pull the piston up, you get the opposite result, liquid evaporates into vapor. At every moment a quantity of liquid is breaking loose from the surface and turning into vapor. At the same time, a quantity of vapor is returning to the liquid phase. So the graph is really a simple phase diagram and we are looking at the effects of phase equilibrium which exists between a liquid and vapor. The liquid evaporates and molecules of vapor condense. When rates of evaporation and condensation are equal, you have an equilibrium. No visible change seems to be occurring, but on the molecular level, a balance exists.

Reed extended the principles of phase equilibrium to the $\text{N}_2\text{O}_4\text{---NO}_2$ reaction.

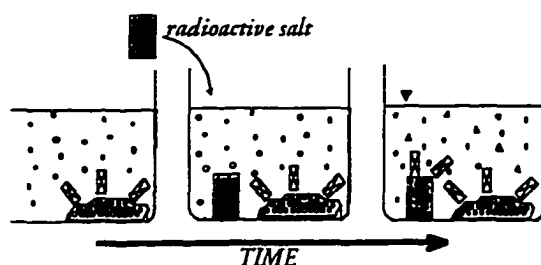
(Explanation associated with qualitative analysis.)

Conceptual

Henry: What is chemical equilibrium? Equilibrium is the condition of a chemical reaction in which the rate of formation of products from reactants equals the rate of formation of reactants from products.



Henry: The arrows stress that this is a dynamic state. This is a very important concept that many students have problems with. It means that when a reaction has received a state of equilibrium, the forward and backward reactions have not stopped at the molecular level, reactant particles collide and form product species, product species collide and reform reactant species. Once equilibrium has been reached it can be upset only by factors that affect the forward and reverse reactions differently. Catalysts remember affect both rates the same. It speeds them up.



Henry: This is a saturated solution of salt. In this case no additional salt dissolves. Imagine that you add five grams of radioactive salt ($^{24}\text{Na}^{38}\text{Cl}$). What happens? Well, you add five grams of solid salt that doesn't disappear. In reality, some sodium and chloride ions go into solution and this alters precipitate out? This goes against our intuition, but you can prove it scientifically by taking a sample of water. After a while, the sample will contain a low level of radioactivity. What has happened? Over time, radioactive salt distributes itself throughout the system even though the salt you added hasn't dissolved. How do you explain this? The forward and reverse reactions occur constantly, but at the same rate.

(Explanation associated with qualitative analysis and visual analogy.)

Dynamic Equilibrium

Traditional

Hoffman: We may think that chemical reactions go in one direction from reactants to products (A → B). At the same time, however, we can have the opposing reaction (B → A). Let's look at an example. Let's say we have this reaction plotted on a graph as a function of time. We introduce a mole of N₂O₄, which is a colorless gas, into a 1 liter container. We see the concentration drop over time as the reaction proceeds. NO₂ concentration will begin to increase. When the concentration of reactant and product no longer change, we say the system is at equilibrium. Concentration and temperature are factors that influence the system.

This principle is shown with a simple calculation of the

$\frac{[\text{NO}_2]^2}{\text{N}_2\text{O}_4}$

ratio value at equilibrium. From experiments we get these values (refers to text).

	Initial N ₂ O ₄	Conc. NO ₂	Equilibrium N ₂ O ₄	Conc. NO ₂
forward rxn	1.00	0	0.80	0.40
reverse rxn	0	2.00	0.80	0.40

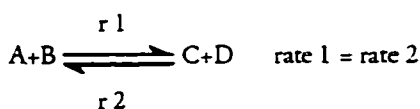
$$\frac{[\text{NO}_2]^2}{[\text{N}_2\text{O}_4]} = \frac{[0.40] \times [0.40]}{[.80]} = 0.20$$

The constant value of the ratio shows we start with different initial values and logically enough arrive at an equilibrium state.

(Explanation associated with quantitative analysis.)

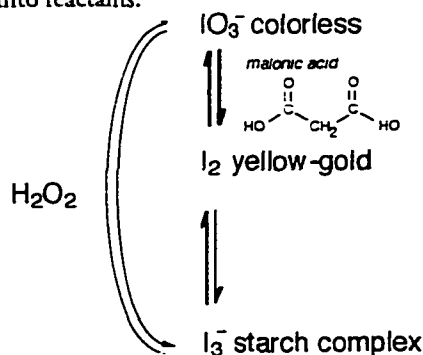
Conceptual

Collins: Very few chemical reactions go to products as written. We often have examples where the backward reaction also proceeds to some extent (referring to overhead). Equilibrium is reached when the rates of both the forward and reverse reactions are equal. This is what is meant by a dynamic equilibrium. This is a general reaction that includes that idea.



O.K. Let's think about what this means at the molecular level. The picture I want you to get is this: in this reaction the molecules of A collide with B molecules and form C and D molecules. The reaction proceeds at a certain rate which is r1. Now let's imagine we have the reaction in a closed container so molecules don't escape. What happens? When C and D begin to form, collisions occur between them – and they begin to reform A and B. This reaction is going on at some rate, say r2. so this means that the concentrations of molecules will increase too. Eventually, the rate of the reverse reaction will equal the rate of the forward reaction. A and B molecules will form at the same rate as C and D molecules. Then you have an equilibrium system. This is what this equilibrium means. Both forward and reverse reactions continue to take place at the same rate, but there is no change in the concentration of the molecules. O.K? Does everybody see that?

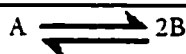
Collins: O.K. Here's one more demonstration for equilibrium. We're going to do one that is shown here on the overhead called the oscillating iodine reaction. Let's get this going, O.K? It's going to oscillate between a blue color and a golden color. What's happening here is it's a combination of equilibrium and kinetics. This shows the principle of reversibility that we discussed earlier, and reactants change into products and products into reactants.



(Explanation associated with qualitative analysis and demonstration.)

Dynamic Equilibrium

Traditional



If a gas is introduced into a closed container at a specific temperature, a portion of A decomposes by way of the general reaction. As the molar concentration of gas B builds up, some of it associates back into A. Eventually, the rates of the competing reactions become equal and the system is at a position of chemical equilibrium.

if.....the position of an equilibrium system is such that the concentrations of reactants and products can be expressed in a fixed numerical ratio in moles per liter at a fixed temperature,

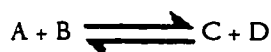
and.....if this is a characteristic property of chemical equilibria,

then.....the relationship should hold for any equilibrium at a specified temperature despite the composition of reactants and products,

and if...the concentration of reactants and products are varied in different system and the equilibrium positions are determined in all cases and found to be the same,

then.... the ratio is a characteristic of equilibrium system at a fixed temperature and can be expressed as a mathematical quotient.

Both teachers translated this general principle into an algebraic expression for the general reaction:



where A, B, C and D represent different substances and a, b, c, and d are coefficients of the balanced equation

$$K_{eq} = \frac{[C]^c \times [D]^d}{[A]^a \times [B]^b}$$

(Explanation associated with quantitative analysis.)

Conceptual

If at equilibrium:

$$K_{eq} = \frac{[C]^c [D]^d}{[A]^a [B]^b}$$

If not, then use:

$$Q = \frac{[C]^c [D]^d}{[A]^a [B]^b}$$

Henry: Look at this slide. It shows what a mathematical expression that you will be using a lot in your calculations. It is called the equilibrium constant and it is derived from the so-called law of mass action which says that the concentrations of reacting species are related to the rates of reaction. In the expression for the equilibrium constant, note that the products make up the numerator and reactants make up the denominator. Also, each concentration of the reactants and products is raised to a power equal to the number of moles of that species in the balanced reaction. The fact that it is possible to write an equilibrium constant which has a definite numerical value for an equilibrium reaction means that if we start with a mixture containing only molecules of reactants A and B, a reaction must occur to form products C and D, O.K? A catalyst can alter the reaction but since it is not a reactant or product in the overall reaction, it can't change the constant value. In order to achieve equilibrium, the concentration of C and D molecules must increase by some amount from the initial amount of zero; the concentrations of A and B must decrease by a corresponding amount. If we start with a mixture of only C and D, the reverse reaction must occur until the concentration ratio satisfies the equilibrium constant value. What we are doing, then, is comparing the concentration quotient (Q) to concentration ratio that must be established at equilibrium (K_{eq}). This is the basis for predicting which way a reaction will go mathematically, by comparing Q to K_{eq}. So, if Q > K_{eq}, the reaction goes to the left to make more reactants, if Q < K_{eq}, the reaction goes to the right to make more product.

Collins: Equilibrium constants have two important functions. They can tell us whether a reaction will be spontaneous under given conditions and in which direction. They also let us calculate the concentration of products and reactants at equilibrium. Its important to remember when we talk about these math ratios to remember that a chemical equation tells us about reacting molecules. Whatever ratio exists between particles of reactants and products.... It also exists between moles. The mole really expands this up to lab-size quantities, O.K. When you compare Q to K_{eq} you can tell which way a reaction will go to reach equilibrium.

(Explanation associated with qualitative analysis.)

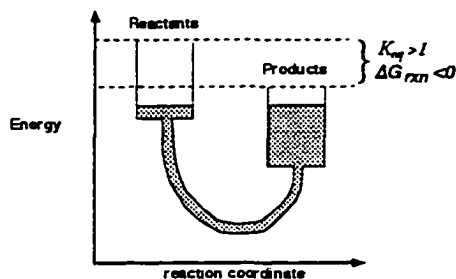
Equilibrium Constant

Traditional

Reed: There is a principle involved in these systems. In an equilibrium system when disturbed, it will try to undo change imposed on it. This applies to other things more general than chemistry. Chemistry is really simpler than most things. For example, think of the money market and how the law of supply and demand operates. That's a type of economic equilibrium. The principle is simpler than that. All you have to do is apply the principle which says whatever you do to it, it will try to undo it. Let's try some of the other cases. Not using a mathematical approach, but just believing in Le Chatelier's principle. Part 13 of the problem says what happens if we increase methane pressure? That is we add more methane. (It shifts back to left)

(Explanation associated with quantitative analysis and verbal analogy.)

Conceptual



Henry: Now we come to a very, very important point. This is perhaps the most important qualitative concept that you will learn this semester for chemical reactions. Listen carefully. We're going to do some numerical problems later, but what I really want you to understand and to be able to qualitatively predict is the qualitative concept and how it affects the performance of chemical reactions. It's called Le Chatelier's principle, named for the French Chemist. When a system in a state of equilibrium is acted upon by some outside stress, the system will, if possible, shift to a new equilibrium position to offset the effect of the stress. (Referring to the container graphic) Now I'm going to disturb this equilibrium system. This represents $K_{eq} > 1$, we are making more product than reactants, O.K.? Look what happens if I add more product – H_2O – now I'm getting a flow backwards so we're making more reactants but the same amount of energy exists.

This is what Le Chatelier's principle informs us qualitatively. Again, if I'm adding more reactants to the reactant side, I'm disturbing the equilibrium so the net reaction shift is to make more product. Now look again at the level in the two containers. It helps to understand if you relate it also to thermodynamics. If the products are high in energy, it will flow back to make more lower energy reactants. So if there's a big energy difference, you don't worry too much about the equilibrium system since it's already going to the side with the lower energy level. Remember, thermodynamics doesn't tell you how fast the reaction is going. Now let's think of temperature change. What happens depends on whether the reaction gives off heat or uses heat. If exothermic, heat is a product. Now increase the temperature. You add more product, so the equilibrium shifts back to make reactants. If you remove heat, it shifts forward. This can help you remember the key concepts.

(Explanation associated with qualitative analysis and visual analogy.)

Le Chatelier's Principle

Traditional

Hoffman: If we start with a mixture of two gases and we want to know whether a reaction will proceed in the forward or reverse direction, the decision can be made if the concentration ratio is compared to that which has to be established at equilibrium. For, example, if at 100° C the equilibrium constant is

$$K_c = \frac{[\text{NO}_2]^2}{[\text{N}_2\text{O}_4]} = .20\text{m}$$

and we actually have 2 moles of N_2O_4 and 2 moles of NO_2 in a 1 liter container, then

$$Q_c = \frac{[\text{NO}_2]^2}{[\text{N}_2\text{O}_4]} = 2.00\text{m}$$

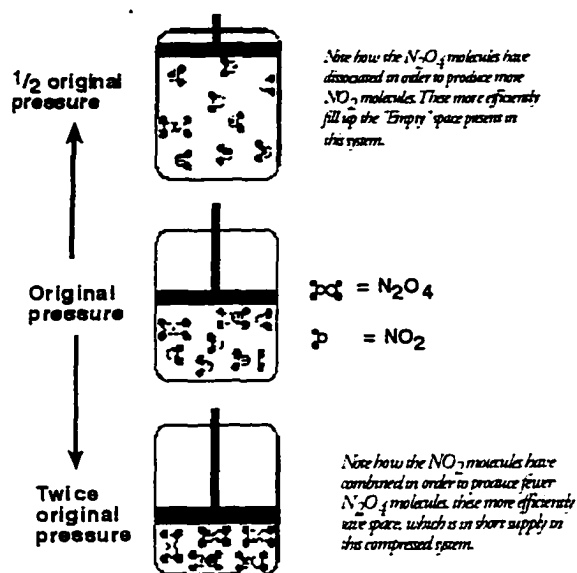
The value of Q/K tells you which direction it goes. Q is bigger than K , so it goes backwards.

Referring back to the earlier dinitrogen tetroxide - nitrogen oxide reaction, Dr. Hoffman discussed the effects of pressure increase on an equilibrium system.

Hoffman: This would make a good demonstration, but I can't do it for safety reasons. Let's suppose we put this into a container except that it is transparent so we can watch the color. Now we increase pressure and reduce the volume of the gases. When NO_2 changes to N_2O_4 , the number of moles is halved. If the volume is constant, the pressure depends on the number of moles present. Therefore, when NO_2 molecules combine, the pressure decreases. So when we increase the pressure on the system, the equilibrium shifts to make fewer moles of gases. The color changes from brown to colorless. When a system is at equilibrium and conditions are changed, the system adjusts to accommodate the conditions.

(Explanation associated with quantitative analysis.)

Conceptual



Collins: When we're dealing with gases, pressure has an effect on equilibrium under certain conditions. Let's look at the reaction N_2O_4 dissociates to give 2 NO_2 in a one liter container. We have at equilibrium a N_2O_4 concentration of .0045m and NO_2 at .0310m. Now push the piston down and halve the volume from one liter to .5 liter. What happens to the concentrations of the gases? (Student responds) Right. The concentration of gases are now doubled. Does this represent an equilibrium? No. I have just disturbed the equilibrium system. The reason its' disturbed is because I don't have the same number of gas phase molecules on either side on the reaction. If you have the same number of gas phase molecules on either side on the equation - everybody look at the equation - then pressure will not have an effect. Note that I'm making two product molecules for one reactant. If I increase the volume, I decrease the pressure - what happens? (Student response) that's right - nature wants to cooperate by filling up space. This favors the product side, doesn't it? You get two molecules, it favors the side that has fewer - it combines two molecules to take up less space, so you favor the side of the equilibrium that has fewer molecules. The equilibrium shifts to that side. This is an example of Le Chatelier's principle.

(Explanation associated with qualitative analysis and visual analogy.)

Le Chatelier's Principle

APPENDIX D

PROBLEM SOLVING METHODS

The intent of this section is to disclose the mechanisms of problem solving used in traditional and conceptual classes at a level of detail sufficient to clearly indicate their similarities and differences.

If traditional courses emphasized mathematical competencies, the conceptual courses emphasized qualitative knowledge as the foundation of mathematical formalism. The simplest distinction is that traditional chemistry exercised the capacity to translate a problem expressed in words into an algebraic expression assuming that this ability represented comprehension of underlying principles. By contrast, conceptual chemistry encouraged students to construct a mathematical expression that was equivalent to their constructed qualitative conception of the problem. Both approaches to problem solving are documented from teachers' problem solving explanations.

One of the most powerful, versatile, and widely taught algorithms in chemistry is dimensional analysis or the factor label method. The basic notion is to treat the various quantities in a chemical equation as quantities that follow the rules of algebra. Traditional problem solving is viewed as an attempt to determine the value of one or more unknown quantities by getting the units to cancel. The procedure was described in the text and was the approach to problem solving most often demonstrated in traditional chemistry in this study.

By contrast, the method employed in conceptual chemistry was based upon an informal analysis by the conceptual teachers of the process and mechanism required for skillful problem solving as well as the difficulties students frequently encounter. The conceptual teachers assumed that students' success in problem solving was affected by their ability to qualitatively analyze a problem before proceeding to actual calculations and the generation of a numerical answer. For example, solving the following equilibrium problems involved first inferring the direction of change that an equilibrium will shift depending upon specific problem conditions. When sufficient information has been generated to solve the abstract, qualitative problem, the solution is seen to generate a quantitative equation to solve the original problem.

Henry demonstrated this approach to qualitative analysis in the first problem. Reed suggested the use of this method a number of times in his discussions of theoretical concepts. An example is his explanation of Le Chatelier's principle. However,

he opted to use the textbook's quantitative method of analysis in actual problem solving examples. In the second example Hoffman applied the factor label method to solve a problem almost identical to Henry's.

The problems required a calculation of the value of an equilibrium constant when the initial reactant and product concentrations and one equilibrium concentration are known values. In the first example from Henry's conceptual class, the equilibrium system is first described in qualitative terms. In this instance, a verbal description is provided; in other examples, the problem is described both verbally and pictorially.

These qualitative descriptions appeared to serve the purpose of accessing important declarative information. This served to extend students understanding, not only of the solution steps, but also of the physical entities on which the problem was based. By applying the relevant theoretical concepts, the outcome can then be qualitatively predicted before calculations. This initial analysis guided the subsequent construction of a mathematical description as is demonstrated by Henry's solution as follows:

Henry: O.K....I've given you all real number concentrations for the reactants and products. If I tell you that at equilibrium $\text{SO}_2 = 3\text{M}$, I've given you all the initial concentrations and one equilibrium concentration. From this information, you can calculate K_{eq} , the equilibrium constant. It's actually very simple if you understand stoichiometry which is constant ratios of reactants are going to react to make certain amounts of product. So the first thing you have to do is figure out which way the reaction is going to go to work out your answer. Now we don't know what the equilibrium constant is, so we can't use the reaction quotient. We only use the reaction quotient (Q) to figure out which way a reaction is going to go if I give you a numerical value for K. But you do have an equilibrium value. At equilibrium $[\text{SO}_2]$ is going to be 3 mole. Initially the $[\text{SO}_2]$ concentration was 4 moles, but it's dropping down to 3 moles. That means the reactants are reacting to make more product. So we're going to make more product and the reaction shifts to the right.

Note that the qualitative description has incorporated much of the information needed for selection in the mathematical equation. In a very basic sense, qualitative thinking guides quantitative. As the solution proceeds, Henry begins to organize the information into a simple table, a device that was used consistently in both conceptual classes during quantitative problem solving.

Henry: This information now tells us which way we can add or subtract our X's. We're going to lose reactants. So this means...initial concentrations minus coefficients times X on the other side of the equation we have initial

concentration plus the coefficient times X. I usually write my initial conditions above the reaction. At equilibrium, I also write down my algebraic expression below the reaction. O.K. Remember at equilibrium, I'm going to lose some reactants to make products. So the algebra is the initial concentration 4 molar minus the coefficient 2 times X. (so $4 - 2x$). For oxygen, it's going to be the initial concentration 4 minus X because oxygen has a coefficient of one (1). Over on the product side, we're making more product so the initial concentration is 6 moles plus 2, the coefficient, times X. Normally, at this point, we would take this and plug it in to our equilibrium expression which is equal to some numerical value of K_{eq} , and then solve for X. But I'm asking you to solve for K_{eq} . What I've given you is a way to mathematically solve for X. I've given you the equilibrium concentration of one of the reactants or products. By knowing the equilibrium concentration of one factor, you can calculate everything else once you have set up your algebraic relationships.

As a last step, Henry constructs a purely mathematical description of the equilibrium.

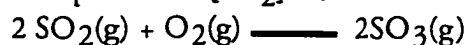
What I have here now is 4 minus $2x$ for the SO_2 concentration at equilibrium and I've given you an equilibrium concentration (3M). So, develop your algebraic expression: ($4 - 2x = 3M$) I don't know the values for $[O_2]$ and $[SO_2]$, but once I've solved for X, I can then calculate those values at equilibrium. After I determine all their values, I can then plug these into the equilibrium expression to solve for K_{eq} . This is really a stoichiometry problem, although setting up the algebraic part is very important and that comes from your knowledge of how to set up the equilibrium reaction. Now, double check your algebra, then plug your values into the equilibrium expression.

In the conceptual classes, a problem example invariably included this explicit sequence of qualitative and quantitative analysis.

Calculate K_{eq} for the following reaction:

The initial concentrations are: $[SO_2] = 4m$, $[O_2] = 4m$, $[SO_3] = 6m$.

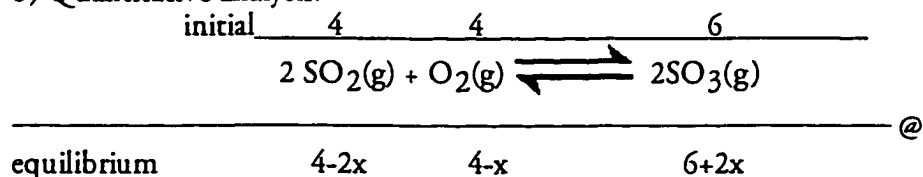
At equilibrium $[SO_2] = 3m$.



a) Qualitative analysis:

We have initial and one final equation condition to tell us which way the reaction is going to shift at equilibrium. Initial $[SO_2] = 4m$, at equilibrium $[SO_2] = 3m$. therefore, the reaction is proceeding to make more product and less reactant. This tells us which way we can add or subtract our x's in our algebraic expression.

b) Quantitative analysis:



@ equilibrium
(given)

	3	?	?
--	---	---	---

c) Let $4-2x = 3$ and solve for x :

$$4-2x = 3 \rightarrow 2x = 1 \rightarrow x = 0.5$$

@ equilibrium

	4-2x	4-x	6+2x
3m	3.5m	7m	

Finally, substitute final values into the equilibrium expression to solve for K_{eq} :

$$K_{eq} = \frac{[\text{SO}_3]^2}{[\text{SO}_2]^2[\text{O}_2]} = \frac{(7\text{m})^2}{(3\text{m})^2(3.5\text{m})} = 1.6\text{m}^{-1}$$

(Problem solving method in conceptual chemistry)

Traditional

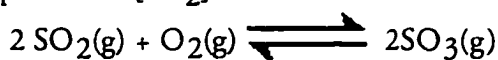
Hoffman's solution of the problem uses only the dimensional analysis method with minimal qualitative explanation. The following is an excerpt from a series of problems he worked during one class session.

Hoffman: O.K. Let's work through this example. We want to calculate the value of the equilibrium constant. As we've seen, this is a ratio of equilibrium product concentration to equilibrium reactant concentration. So to determine the value of K_c , we have to find each equilibrium concentration. This problem gives you the initial concentrations and one equilibrium concentration. So we can calculate the others. (Works through example on board) O.K. The moles per liter of SO_2 reacted is equal to... The initial number of moles of SO_2 minus the number of moles of SO_2 at equilibrium. That gives us....(writes on board) From the reaction stoichiometry, we can calculate the moles of O_2 at equilibrium. This is equal to the initial number of moles of O_2 minus the moles that reacted. The moles of SO_3 at equilibrium equals the initial number minus the moles of SO_3 produced because we made less product. Now you can plug the values into the equilibrium expression and calculate your equilibrium constant value.

Calculate K_{eq} for the following reaction:

The initial concentrations are: $[\text{SO}_2] = 3\text{m}$, $[\text{O}_2] = 6\text{m}$, $[\text{SO}_3] = 1\text{m}$.

At equilibrium $[\text{SO}_2] = 1.4\text{m}$.



$$K_{eq} = \frac{[\text{SO}_3]^2}{[\text{SO}_2]^2 [\text{O}_2]}$$

$$[\text{SO}_3]_{\text{prod}} = [\text{SO}_3]_{\text{eq}} - [\text{SO}_3]_0 = 1.40 - 1.0 = .4$$

$$[\text{SO}_2]_{\text{con}} = [\text{SO}_3] \cdot \frac{2\text{m SO}_2}{2\text{m SO}_3} = .4\text{m}$$

$$[\text{O}_2]_{\text{con}} = [\text{SO}_3] \cdot \frac{1\text{m O}_2}{2\text{m SO}_3} = .2\text{m}$$

$$[\text{SO}_2]_{\text{eq}} = [\text{SO}_2]_0 - [\text{SO}_2]_{\text{con}} = 3.00 - .4 = 2.6\text{m}$$

$$[\text{O}_2]_{\text{eq}} = [\text{O}_2]_0 - [\text{O}_2]_{\text{con}} = 6.00 - .2 = 5.8$$

$$K_{\text{eq}} = \frac{[\text{SO}_3]^2}{[\text{SO}_2]^2 [\text{O}_2]} = \frac{[1.40]^2}{[2.6]^2 [5.8]} = .05\text{m}^{-1}$$

(Problem solving method in traditional chemistry)

APPENDIX E
CHEMISTRY TESTS
(Equilibrium)

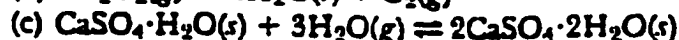
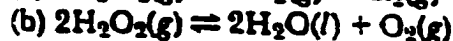
Hoffman

CHEM 1202
General Chemistry
7th March, 1994

SECOND EXAMINATION

1. Turn this page only when instructed to do so.
2. Write your name on the answer sheet after the questions. Do this at the beginning of the examination because at the end no time will be allowed for this.
3. Remove the cover from your calculator.
4. Do not exceed the space given for an answer.
5. Do not use a pencil.
6. When you are finished, hand in only the answer sheet and keep the questions.
7. The use of calculators with extensive storage capacity is forbidden.

17-5. Write the equilibrium-constant expression (K_c) for each of the following equations:



What are the units of K_c in each case?

17-10. The decomposition of phosphorus pentachloride is described by



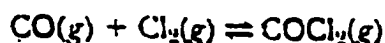
A sample of PCl_5 at an initial concentration of 1.10 M is placed in a reaction vessel held at 250°C. When equilibrium is attained, the concentration of PCl_5 is 0.33 M. Calculate K_c for the reaction.

17-14. Nitrogen dioxide decomposes at high temperatures according to



Suppose initially we have pure $\text{NO}_2(g)$ at 1000 K and 0.500 atm. If the total pressure is 0.732 atm when equilibrium is reached, what is the value of K_p ?

17-26. Suppose that 5.00-mol of $\text{CO}(g)$ is mixed with 2.50 mol of $\text{Cl}_2(g)$ in a 10.0-L reaction vessel and the following reaction attains equilibrium:



Given that $K_c = 4.0 \text{ M}^{-1}$, calculate the equilibrium values of $[\text{CO}]$, $[\text{Cl}_2]$, and $[\text{COCl}_2]$.

17-38. For the chemical equilibrium



predict the way in which the equilibrium will shift in response to each of the following changes in conditions (if the equilibrium is unaffected by the change, then write *no change*):

(a) increase in temperature

(b) increase in reaction volume

(c) removal of $\text{Ni}(\text{CO})_4(g)$

(d) addition of $\text{Ni}(s)$

17-47. Consider the reaction described by



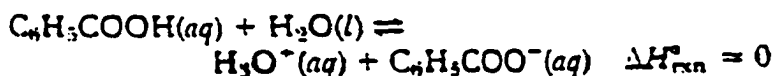
An equilibrium mixture of these gases has the partial pressures $P_{\text{CO}} = 512$ torr, $P_{\text{H}_2\text{O}} = 77$ torr, $P_{\text{H}_2} = 192$ torr, and $P_{\text{CO}_2} = 384$ torr. If the volume of the reaction container is doubled, then what will the new values of the partial pressures be?

18-9. Calculate the pOH and the pH of an aqueous solution prepared by dissolving 2.00 g of KOH pellets in water and diluting to a final volume of 0.500 L.

18-15. The pH of human blood is fairly constant at 7.4. Calculate the hydronium ion concentration and the hydroxide ion concentration in human blood at 25°C.

18-23. The value of K_a in water at 25°C for benzoic acid, $\text{C}_6\text{H}_5\text{COOH}$, is 6.46×10^{-5} M. Calculate the pH and the concentration of the other species in a 0.020 M aqueous solution of $\text{C}_6\text{H}_5\text{COOH}$.

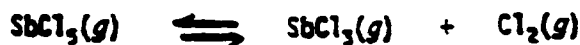
18-37. Use Le Châtelier's principle to predict the direction in which the following equilibrium shifts in response to the indicated change in conditions:



- evaporation of water from the solution at a fixed temperature
- decrease in the temperature of the solution
- addition of $\text{KC}_6\text{H}_5\text{COO}$
- addition of $\text{NH}_3(\text{g})$
- addition of $\text{HCl}(\text{g})$

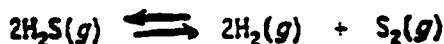
CHEMISTRY 1202
Second Test

1. Antimony pentachloride decomposes in the gas phase according to



If initial concentrations are $[\text{SbCl}_5(g)]_0 = 0.200\text{M}$, $[\text{SbCl}_3(g)]_0 = 0.150$, and $[\text{Cl}_2(g)]_0 = 0.00\text{M}$, and the equilibrium concentration of $\text{Cl}_2(g)$ is 0.095M , what is the equilibrium concentration of $\text{SbCl}_3(g)$?

- a) 0.200M b) 0.095M c) 0.00M d) 0.105M e) 0.295M
2. Concerning the equilibrium $\text{ZnO}(s) + \text{CO}(g) \rightleftharpoons \text{Zn}(l) + \text{CO}_2(g)$, which statement about the equilibrium constant expression is false:
- a) K_p is dimensionless b) $K_p = K_c$ c) K_p depends on temperature
d) denominator ("downstairs") is $[\text{ZnO}][\text{CO}]$ e) numerator is $[\text{CO}_2]$
3. A certain reaction proceeds almost to complete conversion of reactants to products. If K_c for the reaction is one of the following numbers, which is the most reasonable?
- a) 0.001 b) 1.00 c) 1000
4. Consider the equilibrium $2\text{NO}(g) + \text{Br}_2(g) \rightleftharpoons 2\text{NOBr}(g)$ to be established. Two changes are under consideration:
(I) Adding more $\text{Br}_2(g)$ (II) Reducing volume of the container
Which would produce more $\text{NOBr}(g)$ than was present before the change?
- a) Both b) Only I c) Only II d) Neither
5. The reaction $2\text{NO} + \text{Br}_2 \rightarrow 2\text{NOBr}$ is exothermic (see previous problem). What temperature change would increase the concentration of NOBr at equilibrium?
- a) Raising the temperature b) Lowering the temperature
c) Temperature would not affect this equilibrium.
6. For the equilibrium $\text{CH}_4(g) + \text{H}_2\text{O}(g) \rightleftharpoons \text{CO}(g) + 3\text{H}_2(g)$, the following equilibrium pressures were obtained:
- CH_4 : 0.31atm H_2O : 0.83atm CO : 0.57atm H_2 : 2.26atm
- What is the value of K_p for this equilibrium?
- a) 5.2 atm² b) 9.4 atm² c) 18 atm² d) 26 atm² e) 41 atm²
7. Hydrogen sulfide decomposes at 1400 K according to



From initially pure H_2S at a pressure of 0.956 atm, when equilibrium has been reached, the total pressure is 1.26 atm. What is K_p for the reaction?

- a) 0.57 atm b) 0.93 atm c) 2.7 atm d) 8.4 atm e) 17 atm

8. At 300°C, K_c for the equilibrium $\text{PCl}_5(g) + \text{Cl}_2(g) \rightleftharpoons \text{PCl}_3(g)$ is 4.1 M^{-1} . Originally 1.0 mol each of $\text{PCl}_5(g)$ and $\text{Cl}_2(g)$ were placed in a 5.0-L flask at 300°C. What is the equilibrium concentration of PCl_3 ?
 a) 1.0M b) 0.83M c) 0.57M d) 0.23M e) 0.070M
9. $K_p = 0.108 \text{ atm}^2$ for the decomposition at 25°C of ammonium hydrogen sulfide,

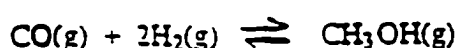
$$\text{NH}_4\text{HS}(s) \rightleftharpoons \text{NH}_3(g) + \text{H}_2\text{S}(g)$$
 What is the total gas pressure in equilibrium with $\text{NH}_4\text{HS}(s)$ at 25°C?
 a) 0.11 atm b) 0.41 atm c) 0.66 atm d) 0.032 atm e) 1.0 atm
10. What is K_c at 300°C for $\text{PCl}_5(g) \rightleftharpoons \text{PCl}_3(g) + \text{Cl}_2(g)$? See Prob. 8.
 a) 4.1 M b) 0.24 M c) 8.2 M d) -4.1 M^{-1} e) 1.0 M
11. What is the acid conjugate to the chlorite ion, ClO_2^- ?
 a) ClO_2^{2-} b) ClO_3^- c) HClO_2 d) H_3O^+ e) HCl
12. In the reaction $\text{NH}_4^+(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NH}_3(aq) + \text{H}_3\text{O}^+(aq)$, the ammonium ion is reacting as a(n)
 a) Bronsted-Lowry acid b) Bronsted-Lowry base c) oxidizing agent
 d) reducing agent e) catalyst
13. What is the pH of a 0.50 M solution of perchloric acid, HClO_4 ?
 a) 0.50 b) 1.0 c) 4.0 d) 13.0 e) 0.30
14. What is the pH of a 0.01 M solution of KOH?
 a) 0.01 b) 0.99 c) 2.0 d) 12 e) 14
15. What is the hydronium ion concentration in a solution having a pH of 3.7?
 a) 2.0×10^{-4} b) 4.0×10^{-2} c) 1.0×10^{-7} d) 3.5×10^{-9} e) 3.77
16. Ozone is naturally produced in the stratosphere from O_2 and _____ from the sun.
 a) infrared light b) ultraviolet light c) visible light
17. Which is not a potential hazard of ultraviolet light:
 a) cataracts b) skin cancer c) damage to the immune system
 d) high blood pressure
18. Which element contained in "CFC's" is felt to be responsible for depletion of the ozone layer?
 a) carbon b) fluorine c) chlorine
19. The Freon designation of CH_2ClF is
 a) 211 b) 112 c) 12 d) 22 e) 31

Chemistry 1202-1

Quiz 5 March 5, 1993

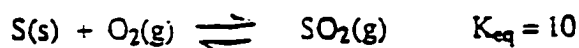
Please answer the following questions **AS NEATLY AS POSSIBLE**-if we cannot read it we won't be able to grade it! Think carefully and use your common sense!

1. Consider the following reaction:

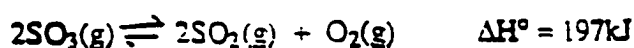


Initially we start with $[\text{CO}] = 10\text{M}$ and $[\text{H}_2] = 11\text{M}$. When the reaction reaches equilibrium there is $5\text{M CH}_3\text{OH}$. Calculate K_{eq} for this reaction. Include units on K_{eq} .

2. Calculate the equilibrium concentrations for each species in the following reaction. The initial ~~concentration~~ of $[\text{SO}_2] = 11\text{M}$. Show your work.



3. What will happen to the number of moles of SO_3 in equilibrium with SO_2 and O_2 in the reaction



in each of the following cases?

- Oxygen is added.
- The pressure is increased by decreasing the volume.
- The temperature is decreased.
- Sulfur dioxide is removed.

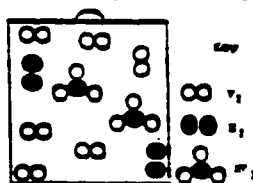
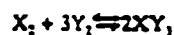
4. In which direction will the position of the equilibrium



be shifted for each of the following changes?

- $\text{H}_2(\text{g})$ is added.
- $\text{I}_2(\text{g})$ is removed.
- $\text{HI}(\text{g})$ is removed.
- The volume of the container is doubled.
- The temperature is increased.

5. Consider the reaction of two gases represented by the following equation.



The system has attained equilibrium under pressure within a closed container. If the pressure is doubled (volume halved), which of the following represents a new state of equilibrium?

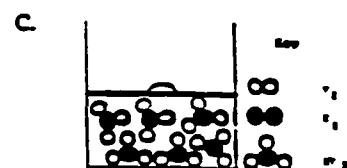
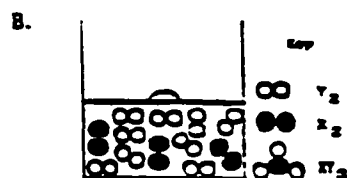
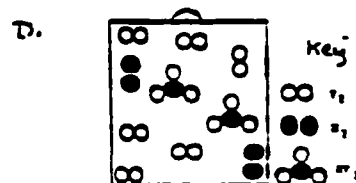
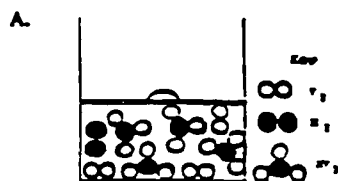


Figure 1. A conceptual question involving the effect of pressure on gaseous equilibrium.

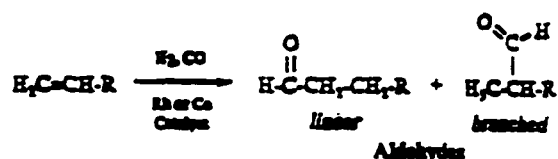
CHEM 1202 – Exam # 2B
Chapters 16, 17 & first part of 18

Please Answer All Questions on the Answer Sheet – Each Question is worth 10 points.

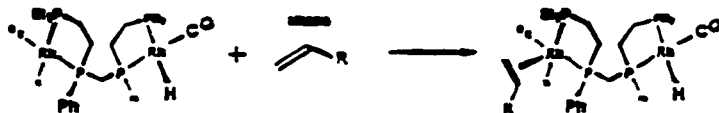
Which of the following statements about the activation energy is **FALSE**?

- The more spontaneous (negative ΔG) a reaction is the lower the activation energy will be.
- The larger and more complex two reacting molecules are, the larger the activation energy is likely to be.
- The activation energy is caused by the need for two reacting molecules to collide in the proper orientation and with the proper energy to allow existing bonds to be broken and new bonds to be formed. Because of this not every collision between two reactant molecules leads to a chemical reaction.
- Increasing the temperature will increase the average velocity of molecules and increase their frequency of collision. This, in turn, will make it more likely that two molecules will react together.
- A reaction with no activation energy will be instantaneous if it is spontaneous (negative ΔG).

2. Hydroformylation is the exothermic reaction of hydrogen, carbon monoxide and carbon-carbon double bonds (alkenes) to produce aldehyde products:



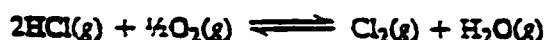
For the bimetallic hydroformylation catalyst that my research group is studying, we believe that the rate determining step is the following:



Based on the information given above, which of the following changes will **most effectively increase the rate** of the overall reaction:

- Increase temperature; increase CO concentration
- Increase temperature; increase alkene concentration; increase catalyst concentration
- Increase H_2 concentration; decrease CO concentration
- Decrease temperature; increase all reactant concentrations
- Decrease temperature; decrease overall reaction pressure

3. The initial conditions for the following reaction are $[\text{HCl}] = 0\text{M}$, $[\text{O}_2] = 0\text{M}$, $[\text{Cl}_2] = 10\text{M}$, and $[\text{H}_2\text{O}] = 10\text{M}$. After the reaction reaches equilibrium, the equilibrium concentration of $[\text{HCl}] = 4\text{M}$. What is K_{eq} for this reaction?



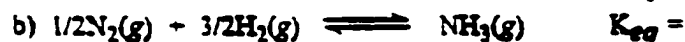
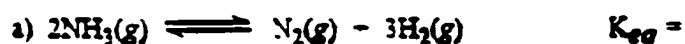
- a) $1 \times 10^{20} \text{ M}^{-1/2}$ b) $4.0 \text{ M}^{-1/2}$ c) $0.25 \text{ M}^{-1/2}$ d) $1 \times 10^{-20} \text{ M}^{-1/2}$

4. (10 pts) Consider the equilibrium: $\text{N}_2\text{O}_4(\text{g}) \rightleftharpoons 2\text{NO}_2(\text{g})$. Initially 0.95 atm of $\text{N}_2\text{O}_4(\text{g})$ is present. When the reaction reaches equilibrium, the *total pressure* is measured to be 1.15 atm. What is the pressure of $\text{N}_2\text{O}_4(\text{g})$ at equilibrium? Show your work.

5 (6 pts) Given the following information:



Calculate the equilibrium constants for the equations shown below (you don't have to show your work):



6 (4 pts) Which equilibrium expression listed below is the correct one for the following reaction:



a) $K_{eq} = \frac{[\text{C}][\text{H}_2\text{O}]}{[\text{CO}][\text{H}_2]}$ b) $K_{eq} = \frac{[\text{CO}][\text{H}_2]}{[\text{C}][\text{H}_2\text{O}]}$ c) $K_{eq} = \frac{1}{[\text{CO}][\text{H}_2]}$ d) $K_{eq} = \frac{[\text{CO}][\text{H}_2]}{[\text{H}_2\text{O}]}$

7 (6 pts) Calculate the concentrations for all species at equilibrium for the following reaction:



The initial concentrations are $[\text{H}_2] = [\text{I}_2] = 0 \text{ M}$, $[\text{HI}] = 4 \text{ M}$. Clearly show your work.

Initially $[H_2] = [I_2] = 4 \text{ M}$, and $[HI] = 0 \text{ M}$. What is the concentration of $[HI]$ at equilibrium?



- a) 0 M b) 2 M c) 4 M d) 8 M e) 16 M

For which of the following reactions will *increasing* the overall *pressure* favor the formation of *reactants*?

- a) $Br_2(g) + I_2(g) \rightleftharpoons 2BrI(g)$ b) $H_2C=CH_2(g) + H_2(g) \rightleftharpoons CH_3CH_3(g)$
 c) $CoCl_4^{2-}(sol) + 6H_2O(sol) \rightleftharpoons Co(H_2O)_6^{2+}(sol) + 4Cl^-(aq)$
 d) $N_2(g) + 2H_2(g) \rightleftharpoons H_2N=NH_2(g)$ e) $CH_3I(sol) + F^-(sol) \rightleftharpoons CH_3F(g) + I^-(sol)$

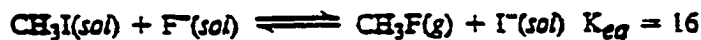
Which of the following common substances is basic?

- a) lemon juice b) Sprite soda c) soap d) coffee e) tea

What is the pH of 1 M HCl (hydrochloric acid)?

- a) 15 b) 10 c) 7 d) 0 e) -10

3. Calculate the equilibrium concentrations for all species in the following reaction. The initial concentrations are $CH_3I = 4 \text{ M}$, $[F^-] = 4 \text{ M}$, $[CH_3F] = 6 \text{ M}$, and $[I^-] = 6 \text{ M}$.



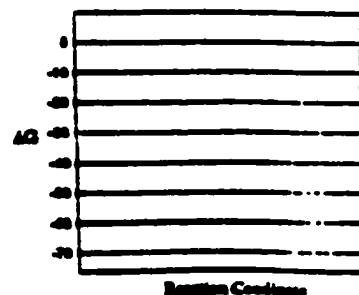
9. Setup (*but do NOT solve*) the following problem to find the concentrations of the reactants and products at equilibrium. Initial conditions: $[A] = 0 \text{ M}$; $[B] = \text{present}$; $[C] = 5 \text{ M}$; $[D] = 5 \text{ M}$. I want to clearly see what the "x" conditions are at equilibrium and the substitution of your "x" values into the equilibrium expression.



10. Draw, in a reasonably accurate fashion, the potential energy curve diagram for the following reaction:

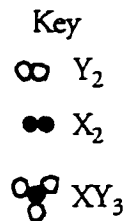
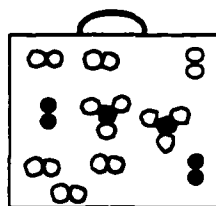
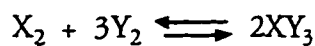


Also draw, using a dashed line, the potential energy curve/diagram one would expect if a *catalyst* was used on this reaction that lowered the activation energy to 50 kJ/mol.

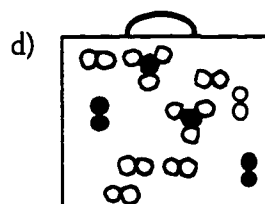
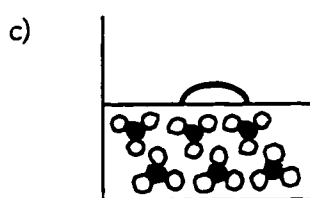
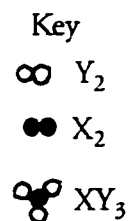
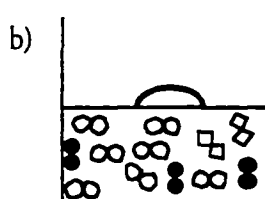
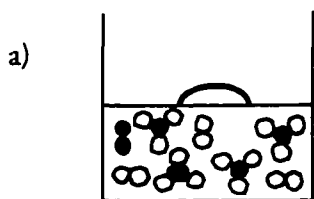


APPENDIX F
Research Instrument

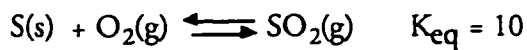
1. Consider the reaction of two gases represented by the following equation.



The system has attained equilibrium under pressure within a closed container. If the pressure is doubled (volume halved), which of the following represents a new state of equilibrium?

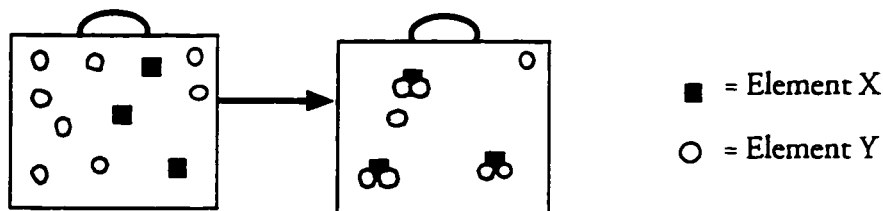


2. What are the equilibrium concentrations for each species in the following reaction?
The initial concentration of SO₂ = 11M. (Show your work).



- a) O₂ = 10M; SO₂ = 1M
- b) O₂ = 10M; SO₂ = 1m, S = 1M
- c) O₂ = 1M; SO₂ = 10M, S = 1M
- d) O₂ = 1M; SO₂ = 10M

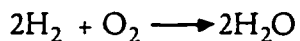
3. The reaction of Element X and Element Y is represented in the following diagram.



Which equation best describes this reaction?

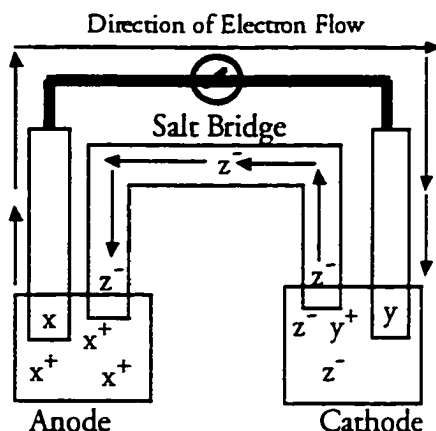
- a) $3X + 8Y \longrightarrow X_3Y_8$
- b) $3X + 6Y \longrightarrow X_3Y_6$
- c) $X + 2Y \longrightarrow XY_2$
- d) $3X + 8Y \longrightarrow 3XY_2 + 2Y$
- e) $X + 4Y \longrightarrow XY_2$

4. A reaction equation can be written to represent the formation of water from hydrogen gas and oxygen gas.



For a mixture of 2 mol H_2 with 9 mol O_2 , what is the limiting reagent and how many moles of the excess reactant would remant unreacted after the reaction is completed? (Show your work).

- a) O_2 1 mol O_2
- b) O_2 1 mol H_2
- c) H_2 8 mol O_2
- d) H_2 1 mol H_2



5. Which of the following represents the oxidation half-reaction of the overall redox reaction occurring in the electrochemical cell?

- $y \longrightarrow y^+ + e^-$
- $x \longrightarrow x^+ + e^-$
- $y^+ + e^- \longrightarrow y$
- $x^+ + e^- \longrightarrow x$

6. Which of the following reactions are redox reactions? Indicate the oxidation states of the atoms that are involved in the redox process.

- $5\text{HNO}_3(\text{aq}) + 3\text{Zn}(\text{s}) \longrightarrow 3\text{Zn}^{2+}(\text{aq}) + 2\text{NO}(\text{g}) + 4\text{H}_2\text{O} + 3\text{NO}_3^-$
- $\text{HCl}(\text{aq}) + \text{NH}_3(\text{aq}) \longrightarrow \text{NH}_4^+(\text{aq}) + \text{Cl}^-(\text{aq})$
 - $\text{N} (+5) \longrightarrow \text{N} (+2); \text{O} (-6) \longrightarrow \text{O} (-2)$
 - $\text{Zn} (0) \longrightarrow \text{Zn} (+2); \text{N} (+5) \longrightarrow \text{N} (+2)$
 - $\text{H} (+1) \longrightarrow \text{H} (+4); \text{Cl} (0) \longrightarrow \text{Cl}^- (-1)$
 - $\text{N} (+6) \longrightarrow \text{N} (+4); \text{Cl} (0) \longrightarrow \text{Cl}^- (-1)$

APPENDIX G

ATTITUDE QUESTIONNAIRE

Please indicate your response to each statement by marking your answer sheet according to the following scale:

- A = Strongly Agree
- B = Agree
- C = Undecided
- D = Disagree
- E = Strongly Disagree

1. This course has been very interesting and enjoyable.
2. The subject matter was presented and explained in a way that helped me understand and learn the important concepts.
3. The exams and grading system in this course were very fair.
4. Anyone who is willing to work has a reasonable chance of making a decent grade in this course.
5. This course was valuable because it helped me to understand and relate chemistry concepts and principles.
6. There was always enough help available outside of class for homework assignments and before exams.
7. This has been a difficult course for me.
8. Explanations and information contained in the textbook were most important in helping me to understand chemistry.
9. The atmosphere in this course was one of competition rather than cooperation among students.
10. Science courses like this one are designed to "weed out the unfit".

11. This course placed too much emphasis on quantitative problem solving and not enough on understanding concepts.
12. The lecture and class notes were most important in helping me understand chemistry.
13. I don't want to take any more chemistry courses like this one.
14. This course would probably motivate students to become chemistry majors.
15. I am interested in taking more courses like this one.
16. I believe that the ability to solve quantitative problems is the best test of an understanding of chemistry concepts.
17. The course showed that chemistry is important in everyday life.
18. The homework assignments were important in helping me learn chemistry.
19. This course was valuable because it helped me to improve my understanding of chemistry problem solving.
20. I like the subject of chemistry more as a result of taking this course.

ATTITUDE QUESTIONNAIRE ANSWER SHEET

Major _____

Freshman ()

Sophomore ()

Junior ()

Senior ()

Male ()

Female ()

A = STRONGLY AGREE

B = AGREE

C = UNDECIDED

D = DISAGREE

E = STRONGLY DISAGREE

1. _____

2. _____

3. _____

4. _____

5. _____

6. _____

7. _____

8. _____

9. _____

10. _____

11. _____

12. _____

13. _____

14. _____

15. _____

16. _____

17. _____

18. _____

19. _____

20. _____

APPENDIX H

BEHAVIOR CODING SYSTEM - CHEMISTRY PROFESSORS

Code	Description of code
C1	followed text organization
C2	omitted sections
C3	added sections
C4	followed class notes
C5	omitted sections
C6	added sections
R1	used spoken language
R2	with written symbols
R3	with visuals (static graphics)
R4	with demonstrations
R5	with concrete models
S1	Whole class
S2	teacher-students
S3	student-student
S4	small group
S5	teacher-students
S6	student-student
T1	multiple choice quantitative
T2	multiple choice qualitative/quantitative
T3	full answer quantitative
T4	full answer qualitative/quantitative
T5	alternative testing

APPENDIX I

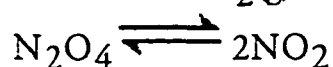
INTERVIEW QUESTIONS - CHEMISTRY PROFESSORS

1. What do you perceive as your role in teaching chemistry?
2. How do you decide what topics to teach? Is the order you teach them in important? Why?
3. How do students learn?
4. When you teach a new concept or topic, what do you usually do to help students understand it? What percentage of your students do you think understand after the first explanation? Why do you think students fail to understand a topic or concept?
5. Is it important for you to know what students understand about a topic before you teach it?
6. What level of student ability do you usually aim for in teaching?
7. How important is it that students present their views or answer questions during class? Why?
8. How do you know when students understand a topic? How do you decide what tests to use to determine this? What do you think of this statement? "The ability to solve a quantitative problem is the best test of a student's understanding of chemistry."
9. What are the main concepts that you teach in order for students to understand the topic of Chemical Equilibrium? What is the best way to teach them?

APPENDIX J

CHEMICAL EQUILIBRIUM -- KEY CONCEPTS AND PROPOSITIONS

The following table is based on the dissociation of Dinitrogen tetroxide, $\text{N}_2\text{O}_4(\text{g})$ into nitrogen dioxide, $\text{NO}_2(\text{g})$.



From Initial Consideration to Equilibrium

1. Molecules of reactant (N_2O_4) disassociate and form product (NO_2).
Molecules of NO_2 collide and reofrm N_2O_4 .
2. The concentration of product $\text{NO}_2(\text{g})$ increases and reactant $\text{N}_2\text{O}_4(\text{g})$ decreases.
3. The rate of the
 - (a) forward reaction decreases as the concentration of reactant decreases.
 - (b) the reverse reaction is initially zero but increases with the concentration of the product.

Chemical Equilibrium

When a state of equilibrium is established

4. The concentrations of all species remain constant with time. Equal concentrations are not necessarily formed.
5. The forward and reverse reactions
 - (a) continue to occur and
 - (b) have equal rates ($r_1=r_2$). This is a dynamic equilibrium.

6. Equilibrium concentrations are based on reaction stoichiometry. When stoichiometrically equivalent amounts of reactants or products react, then the same equilibrium state is attained, starting either from reactants or products side.
7. At equilibrium the relative concentrations of reactants and products are related by the equilibrium law of concentration action or the law of "mass action". This condition may be expressed by a value called the equilibrium constant which takes the form of a quotient.

$$K_{eq} = \frac{\text{Product}}{\text{Reactant}}$$

- (a) the value of K_{eq} (K_c) is equal to a constant at a given temperature.
- (b) the equilibrium product concentrations appear in the numerator and reactant concentrations appear in the denominator
- (c) equilibrium concentrations of each species are raised to a power equal to the stoichiometric coefficients of that species in the equation
- (d) reactants and products that appear as pure solids or pure liquids are not included in the equilibrium expression
- (e) equilibrium constants can also be expressed in terms of partial pressures of gas (K_p). $K_c = K_{eq}$ when the total mol starting either from reactants or products side.
- (f) the reaction quotient (Q_c) is a quantity that has exactly the same algebraic form as the equilibrium constant (K_{eq}) but involves non-equilibrium concentrations. At equilibrium, $Q = 1$ or $Q = K_{eq}$

(g) the direction a reaction will go to reach equilibrium can be predicted by comparing Q to K_{eq}

$Q > K_{eq}$ = reaction goes to left

$Q = K_{eq}$ = equilibrium

$Q < K_{eq}$ = reaction goes to right.

Changing Equilibrium Conditions

8. Le Chatlier's Principle. If a chemical reaction at equilibrium is subjected to a change in conditions that displaces it from equilibrium, then the reaction adjusts toward a new equilibrium state. The reaction proceeds in the direction that at least partially affects the change in conditions.

Changing the concentrations of one of the reactant or product species

After equilibrium has been achieved the N_2O_4 is increased (but the volume remains the same).

9. The concentrations change in such a way that they partially counteract the imposed change. The system adjusts to reduce the concentration of N_2O_4 the NO_2 increases. The concentration ratio (Q) decreases until it becomes equal in magnitude to K_{eq} .
10. When equilibrium is re-established the
- NO_2 will be higher than its initial equilibrium value.
 - N_2O_4 will be higher than its initial equilibrium value.
11. When equilibrium is re-established, the rate of the
- forward and reverse reactions will be equal.
 - forward and reverse reactions will be greater than the initial equilibrium.

12. When equilibrium is re-established, the equilibrium constant (K_{eq}) is the same as under the initial conditions.

Changing the Volume or Pressure of the System

After equilibrium has been achieved, the volume of the system is decreased. A change in volume or pressure has no effect on systems with equal volumes of reactants and products.

13. The concentrations of all gaseous species in the system will increase.
14. The concentrations (and pressures) change to partially counteract the imposed change (increases in concentration of particles). The system adjusts to favor the reaction that produces the smaller number of gaseous particles; the N_2O_4 increases and the NO_2 decreases.
15. When equilibrium is re-established the
- (a) NO_2 will be less than the original equilibrium value.
 - (b) N_2O_4 will be greater than the original equilibrium value.
16. When equilibrium is re-established, the rate of the
- (a) forward and reverse reactions will be equal.
 - (b) forward and reverse reactions will be greater than at the initial equilibrium.
17. When equilibrium is re-established, the equilibrium constant is the same as under the initial conditions.

Changing the temperature of the System

18. After equilibrium has been achieved, the temperature is increased. The concentrations change to partially counteract the imposed change (temperature increase). The system will adjust to favor the endothermic reaction, the NO_2 is increased, the N_2O_4 is decreased.

19. When equilibrium is re-established, the rate of the
 - (a) forward and reverse reactions will be equal.
 - (b) forward and reverse reactions will be greater than at the initial equilibrium.
20. When equilibrium is re-established, the equilibrium constant is smaller than under the initial conditions.

Effect of Adding a Catalyst

After equilibrium has been achieved, a catalyst is added to the system.

21. The rate of the forward reaction is increased.
22. The rate of the reverse reaction is increased.
23. Rates of forward and reverse reactions are equal.
24. The concentrations of N_2O_4 and NO_2 are unchanged.
25. The equilibrium constant is the same as under the initial conditions.

(Adapted from Hackling and Garnett, 1985).

APPENDIX K: ATTITUDE TEST ITEM ANALYSIS
 EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY COURSE: 1202
 Students: 71 Date: Fall, 1992 Mean: 79.9

ITEM ANALYSIS BY PERCENTAGE					
	A	B	C	D	E
1.	49.2	40.8	2.8	4.2	2.8
2.	50.7	32.4	5.6	9.9	1.4
3.	67.6	25.4	5.6	1.4	0.0
4.	78.9	15.5	4.2	1.4	0.0
5.	73.3	23.9	2.8	0.0	0.0
6.	64.8	19.7	12.7	1.4	1.4
7.	2.8	19.7	12.7	42.3	22.5
8.	1.4	2.8	15.5	40.8	39.4
9.	1.4	4.2	7.0	42.3	45.0
10.	2.8	9.9	18.3	38.0	30.9
11.	1.4	7.0	2.8	38.0	50.7
12.	53.5	32.4	5.6	8.4	0.0
13.	18.3	21.1	26.8	18.3	15.5
14.	18.3	22.5	42.3	14.1	4.2
15.	29.6	26.8	25.3	9.9	8.5
16.	12.7	16.9	22.5	29.6	18.3
17.	49.2	26.8	14.1	9.9	0.0
18.	18.3	32.4	21.1	16.9	11.3
19.	42.3	49.2	8.5	0.0	0.0
20.	26.8	32.4	26.8	14.1	0.0

EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 60 Date: Fall, 1992 Mean: 69.8

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E
1.	10.0	36.7	25.0	23.3	5.0
2.	10.0	46.7	25.0	15.0	3.3
3.	35.0	38.3	11.7	3.3	1.7
4.	40.0	38.3	8.3	13.3	0.0
5.	26.7	41.7	18.3	5.0	3.3
6.	16.6	25.0	41.7	10.0	6.6
7.	16.7	18.3	18.3	31.7	5.0
8.	10.0	23.3	16.7	41.7	08.3
9.	1.7	08.3	26.7	40.0	23.3
10.	6.7	28.3	16.6	43.3	5.0
11.	8.3	36.7	13.3	30.0	11.7
12.	13.3	30.0	15.0	40.0	1.7
13.	36.7	21.9	15.0	18.3	10.0
14.	1.7	11.7	36.7	35.0	13.3
15.	6.7	21.7	25.0	20.0	26.7
16.	3.3	30.0	18.3	36.7	11.7
17.	26.7	36.7	25.0	16.6	11.7
18.	10.0	36.7	25.0	16.6	11.7
19.	26.7	30.0	25.0	18.3	0.0
20.	8.3	23.3	35.0	10.0	23.3

EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 63 Date: Spring, 1993 Mean: 72.2

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E
1.	11.1	55.6	19.0	11.1	3.2
2.	15.9	61.9	15.9	4.8	1.6
3.	46.0	34.9	11.1	7.9	0.0
4.	60.3	36.5	4.8	0.0	0.0
5.	42.9	36.5	17.5	3.2	0.0
6.	31.7	36.5	26.9	4.8	0.0
7.	3.2	28.6	6.3	39.7	22.2
8.	6.3	26.9	22.2	38.1	6.3
9.	1.6	4.8	23.8	39.7	30.2
10.	6.3	19.0	20.6	38.1	15.9
11.	3.1	30.2	9.5	30.2	26.9
12.	20.6	49.2	6.3	17.5	6.3
13.	17.5	26.9	20.6	26.9	7.9
14.	4.8	23.8	34.9	26.9	9.5
15.	31.7	38.1	3.2	17.5	9.5
16.	11.1	33.3	17.5	30.1	7.9
17.	47.6	38.1	9.5	4.8	0.0
18.	46.0	34.9	11.1	6.3	1.6
19.	36.5	38.1	15.9	9.5	0.0
20.	26.9	33.3	20.6	17.5	1.6

EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 39 Date: Fall, 1993 Mean: 65.9

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E
1.	10.3	41.0	17.9	20.5	10.3
2.	15.4	38.4	17.9	17.9	12.8
3.	43.6	38.5	12.8	2.6	2.6
4.	43.6	33.3	12.8	7.7	0.0
5.	15.4	38.5	2.6	15.4	02.6
6.	10.3	23.1	17.9	38.5	07.7
7.	15.4	30.8	12.8	30.7	10.3
8.	12.8	30.7	20.5	30.8	0.0
9.	10.3	02.6	5.1	38.5	23.1
10.	10.3	28.2	23.1	23.1	15.4
11.	10.3	28.2	20.5	41.0	0.0
12.	23.1	25.6	15.4	17.9	2.6
13.	38.5	20.5	17.9	12.8	10.3
14.	0.0	12.8	33.3	23.1	30.8
15.	7.7	15.4	20.5	28.2	28.2
16.	5.1	20.5	28.2	35.9	10.2
17.	33.3	46.2	7.7	15.4	2.6
18.	2.6	38.5	23.1	07.7	7.7
19.	10.3	53.8	20.5	5.1	10.3
20.	10.3	25.6	30.8	12.8	20.5

EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 60 Date: Fall, 1994 Mean: 77.3

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E
1.	26.7	48.3	23.3	1.7	0.0
2.	45.0	51.7	1.7	0.0	0.0
3.	86.7	35.0	06.7	1.7	0.0
4.	73.3	23.3	03.3	0.0	0.0
5.	41.7	28.3	10.0	3.3	0.0
6.	60.0	23.3	15.0	38.3	20.0
7.	5.0	21.7	11.7	41.7	10.0
8.	11.9	16.7	23.3	33.0	15.0
9.	0.0	6.7	16.7	30.0	18.0
10.	1.7	18.3	21.7	41.7	15.0
11.	5.0	8.3	15.0	33.0	16.7
12.	63.3	35.0	0.0	1.7	0.0
13.	30.0	26.7	15.0	21.7	6.7
14.	13.3	26.7	48.3	6.7	5.0
15.	13.3	26.7	36.7	11.7	10.0
16.	3.3	16.7	30.0	25.0	8.3
17.	46.7	38.3	10.0	5.0	0.0
18.	58.3	35.0	6.7	0.0	0.0
19.	35.0	46.7	15.0	3.3	0.0
20.	26.7	31.7	26.7	13.3	1.7

EXAMINATION NAME: ATTITUDE
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 19 Date: Spring, 1994 Mean: 54.2

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E
1.	0.0	21.1	47.4	31.6	0.0
2.	10.5	26.3	21.0	31.6	10.5
3.	0.0	21.1	21.1	36.8	21.1
4.	10.5	15.8	21.1	31.6	21.1
5.	0.0	31.6	36.8	21.1	10.5
6.	0.0	4.5	25.3	52.6	18.5
7.	0.0	47.4	21.1	21.1	10.5
8.	0.0	47.4	21.1	31.6	0.0
9.	0.0	21.1	36.8	21.1	0.0
10.	10.5	36.8	31.6	21.1	0.0
11.	0.0	63.2	26.3	10.5	0.0
12.	0.0	26.3	42.1	10.5	0.0
13.	21.0	36.8	42.1	0.0	0.0
14.	10.5	10.5	36.8	42.1	0.0
15.	10.5	10.5	42.1	31.6	5.2
16.	63.2	21.1	5.2	10.5	0.0
17.	31.6	26.3	15.8	10.5	15.8
18.	0.0	42.1	15.8	31.6	10.5
19.	31.6	21.1	21.1	15.8	10.5
20.	31.6	10.5	26.3	26.3	5.2

APPENDIX L: FINAL EXAM ITEM ANALYSIS
 EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY COURSE: 1202
 Students: 177 Date: Fall, 1992
 Mean: 56.33 Std Dev: 14.91

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	0.8	4.6	92.7	1.2	0.6	0.0
2.	4.2	13.1	23.7	29.7	29.3	0.0
3.	59.9	30.8	3.5	1.9	4.0	0.0
4.	34.9	39.1	11.0	11.2	3.7	0.0
5.	6.2	58.2	22.9	10.4	2.1	0.2
6.	15.6	33.9	13.5	33.5	3.3	0.2
7.	44.3	6.9	17.7	13.9	16.4	0.8
8.	5.8	12.5	61.5	10.8	9.1	0.2
9.	0.4	12.7	61.7	10.2	15.0	0.0
10.	30.8	26.0	28.5	10.8	3.7	0.2
11.	1.7	10.4	12.5	64.0	11.4	0.0
12.	2.9	3.5	35.1	11.6	46.8	0.0
13.	70.7	18.7	7.3	1.2	2.1	0.0
14.	69.0	9.1	6.9	6.0	8.9	0.0
15.	2.3	69.6	7.5	11.4	9.1	0.0
16.	19.5	12.9	51.4	15.8	0.2	0.2
17.	91.1	8.1	12.9	56.8	2.7	0.4
18.	94.2	2.1	2.1	1.0	0.6	0.0
19.	25.8	7.3	62.0	2.1	2.9	0.0

EXAMINATION NAME: FINAL CONTINUED

	A	B	C	D	E	Invalid
20.	21.2	15.6	56.3	4.0	2.9	0.0
21.	3.1	4.0	25.8	3.5	63.6	0.0
22.	7.7	43.9	33.9	11.4	3.1	0.0
23.	13.1	53.2	13.3	20.2	0.2	0.0
24.	6.7	19.5	8.3	25.4	40.1	0.0
25.	3.3	3.3	8.9	6.0	78.4	0.0
26.	38.5	5.6	21.0	31.0	4.0	0.0
27.	12.9	67.4	13.7	4.4	1.7	0.0
28.	17.7	52.2	9.6	5.0	15.6	0.0
29.	81.7	5.6	1.0	8.3	3.3	0.0
30.	15.6	20.6	45.3	4.8	13.7	0.0

EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 227 Date: Fall, 1992
 Mean: 57.19 Std Dev: 14.43

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	1.4	3.6	91.4	2.3	1.4	0.0
2.	1.4	5.9	44.6	36.9	11.3	0.0
3.	31.5	56.8	3.6	2.3	5.9	0.0
4.	43.7	20.7	13.1	17.1	5.4	0.0
5.	6.8	66.2	20.3	5.4	1.4	0.0
6.	21.2	37.4	19.8	16.7	4.1	0.9
7.	45.5	6.3	15.3	16.7	15.3	0.9
8.	7.7	7.2	72.5	5.4	7.2	0.0
9.	0.9	18.9	48.2	9.0	23.0	0.0
10.	23.0	27.9	31.1	12.2	5.4	0.5
11.	2.3	9.5	14.4	65.8	8.1	0.0
12.	1.8	2.7	14.0	5.4	76.1	0.0
13.	56.3	25.7	13.1	2.3	2.7	0.0
14.	82.0	4.1	3.2	5.4	5.4	0.0
15.	2.3	65.3	8.6	13.1	10.8	0.0
16.	34.7	20.3	32.4	11.7	0.5	0.5
17.	30.2	9.0	14.9	40.5	5.0	0.0
18.	95.9	0.0	3.2	0.5	0.5	0.0
19.	28.4	5.9	64.0	0.9	0.9	0.0

EXAMINATION NAME: FINAL CONTINUED

	A	B	C	D	E	Invalid
20.	18.9	11.7	65.3	2.7	1.4	0.0
21.	2.7	4.1	28.4	3.6	61.3	0.0
22.	5.9	65.8	14.9	10.8	2.7	0.0
23.	9.0	84.2	2.3	4.1	0.5	0.0
24.	6.3	32.0	4.1	12.2	45.5	0.0
25.	2.7	2.3	9.5	2.7	82.9	0.0
26.	52.7	6.3	17.1	20.3	3.6	0.0
27.	11.3	72.1	10.4	5.4	0.9	0.0
28.	22.1	52.3	8.6	4.1	13.1	0.0
29.	88.3	1.4	0.9	7.2	2.3	0.0
30.	25.7	31.1	20.3	5.9	17.1	0.0

EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY
 COURSE: 1202
 Students: 24 Date: Spring, 1993
 Mean: 56.48 Std Dev: 15.55

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	0.0	23.8	19.0	52.4	4.8	0.0
2.	9.5	4.8	4.8	81.0	0.0	0.0
3.	4.8	85.7	9.5	0.0	0.0	0.0
4.	19.0	42.9	14.3	19.0	4.8	0.0
5.	0.0	19.0	0.0	71.4	9.5	0.0
6.	33.3	0.0	19.0	19.0	28.6	0.0
7.	33.3	9.5	14.3	19.0	23.8	0.0
8.	0.0	19.0	14.3	66.7	0.0	0.0
9.	14.3	23.8	14.3	47.6	0.0	0.0
10.	47.6	0.0	38.1	14.3	0.0	0.0
11.	81.0	9.5	4.8	0.0	4.8	0.0
12.	0.0	4.8	19.0	76.2	0.0	0.0
13.	42.9	0.0	4.8	52.4	0.0	0.0
14.	19.0	0.0	61.9	0.0	19.0	0.0
15.	19.0	23.8	23.8	0.0	33.3	0.0
16.	33.3	19.9	33.3	9.5	4.8	0.0
17.	9.5	90.5	0.0	0.0	0.0	0.0
18.	4.8	57.1	28.6	9.5	0.0	0.0
19.	19.0	61.9	19.0	0.0	0.0	0.0

EXAMINATION NAME: FINAL CONTINUED

	A	B	C	D	E	Invalid
20.	0.0	76.2	19.0	4.8	0.0	0.0
21.	42.9	4.8	28.6	9.3	14.3	0.0
22.	33.3	9.5	42.9	9.5	4.8	0.0
23.	33.3	9.5	42.9	9.5	4.8	0.0
24.	9.5	0.0	9.5	57.1	23.8	0.0
25.	4.8	71.4	9.5	0.0	14.3	0.0
26.	4.8	0.0	38.1	0.0	57.1	0.0
27.	23.8	4.8	0.0	2;8.6	42.9	0.0
28.	14.3	57.1	9.5	19.0	0.0	0.0
29.	9.5	9.5	81.0	0.0	0.0	0.0
30.	4.8	4.8	9.5	81.0	0.0	0.0
31.	42.9	19.0	19.0	19.0	0.0	0.0
32.	9.5	28.6	4.8	38.1	19.0	0.0
33.	14.3	9.5	0.0	76.2	0.0	0.0
34.	14.3	47.6	14.3	4.8	19.0	0.0
35.	0.0	9.5	0.0	81.0	9.5	0.0
36.	9.5	19.0	4.8	28.6	38.1	0.0

EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY
 COURSE: 1202

Students: 194 Date: Spring, 1993
 Mean: 63.48 Std Dev: 13.35

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	4.8	3.7	13.4	63.1	15.0	0.0
2.	23.0	7.0	7.5	62.6	0.0	0.0
3.	1.1	98.4	0.5	0.0	0.0	0.0
4.	18.2	59.9	4.8	6.4	10.2	0.5
5.	0.0	9.1	0.0	89.8	1.1	0.0
6.	15.5	1.6	3.2	12.8	6.8	0.0
7.	65.8	2.7	11.2	9.1	9.1	2.1
8.	8.6	3.2	13.9	68.4	5.3	0.5
9.	2.1	24.6	7.5	64.2	1.6	0.0
10.	64.7	3.7	28.3	3.2	0.0	0.0
11.	61.5	21.9	15.5	0.5	0.5	0.0
12.	5.9	3.2	9.1	81.3	0.5	0.0
13.	21.9	1.1	1.6	74.3	1.1	0.0
14.	16.0	0.5	67.9	3.7	11.8	0.0
15.	14.4	26.7	8.0	3.2	46.5	1.1
16.	22.5	17.1	35.3	11.2	13.9	0.0
17.	1.1	97.3	0.0	0.5	1.1	0.0
18.	7.0	48.1	39.6	2.1	1.1	0.0
19.	17.6	75.9	4.3	2.1	0.0	0.0

EXAMINATION NAME: FINAL CONTINUED

	A	B	C	D	E	Invalid
20.	8.0	81.3	2.7	6.4	1.6	0.0
21.	32.1	6.4	21.4	7.5	32.6	0.0
22.	16.0	15.0	41.7	22.5	4.8	0.0
23.	23.0	0.5	2.1	0.0	74.3	0.0
24.	1.6	3.7	4.3	86.1	4.3	0.0
25.	2.7	73.3	3.7	5.9	14.4	0.0
26.	0.5	12.8	38.5	1.1	47.1	0.0
27.	4.8	0.5	4.8	18.2	71.7	0.0
28.	18.2	59.9	4.3	17.6	0.0	0.0
29.	17.6	23.5	58.3	0.0	0.5	0.0
30.	8.6	2.7	6.4	81.8	0.5	0.0
31.	66.8	12.3	12.8	7.5	0.0	0.5
32.	11.2	16.6	8.6	47.6	15.5	0.5
33.	9.6	18.2	8.6	58.8	4.3	0.5
34.	23.5	42.2	8.6	14.4	11.2	0.0
35.	0.0	4.3	2.7	87.2	5.9	0.0
36.	19.3	18.7	10.7	28.3	21.9	1.0

EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY COURSE 1202
 Students: 202 Date: Fall, 1994
 Mean: 53.80 Std Sev.: 4.71
 ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	1.1	68.4	20.9	5.9	3.7	0
2.	9.1	5.9	17.6	12.3	55.1	0
3.	11.8	8.6	6.4	36.9	35.8	0.5
4.	13.4	8	9.1	69	0.5	0
5.	30.5	5.9	44.9	12.8	5.9	0
6.	20.9	0.5	62.6	2.1	13.9	0
7.	1.1	27.3	52.9	18.7	0	0
8.	46	26.2	15	9.6	3.2	0
9.	1.6	8	18.7	3.2	68.4	0
10.	10.2	46.5	8	20.9	14.4	0
11.	5.9	7	8	77.5	1.6	0
12.	2.1	96.3	0	0.5	1.1	0
13.	8.6	72.7	13.9	2.7	0.5	1.6
14.	1.6	88.8	2.7	6.4	0.5	0
15.	6.4	9.6	71.7	7	4.3	1.1
16.	9.6	5.9	71.1	5.9	7.5	0
17.	6.4	8	3.2	15	67.4	0
18.	9.6	51.3	16.6	19.3	3.2	0
19.	28.3	25.7	35.8	3.7	5.9	0.5
20.	16	35.8	25.1	19.3	3.2	0.5

EXAMINATION NAME: FINAL CONTINUED

21.	55.1	10.7	2.1	20.3	11.8	0
22.	4.3	10.7	7	3.7	74.3	0
23.	2.7	31	9.6	46	10.2	0.5
24.	19.3	13.9	4.8	12.8	49.2	0
25.	11.2	2.7	75.9	4.3	5.9	0
26.	16.6	21.4	3.7	48.7	9.6	0
27.	0.5	79.7	6.4	9.1	4.3	0
28.	3.2	5.3	10.2	65.8	15.5	0
29.	9.6	10.7	67.9	5.3	6.4	0
30.	45.5	39	11.2	3.7	0.5	0
31.	42.2	4.3	10.7	36.9	5.9	0
32.	29.4	13.9	19.3	21.9	15	0.5
33.	20.3	16.6	50.3	12.8	0	0
34.	17.6	18.7	27.3	17.6	18.7	0
35.	12.3	17.1	6.4	18.7	45.5	0

EXAMINATION NAME: FINAL
 DEPARTMENT: CHEMISTRY
 COURSE 1202

Students: 178 Date: Fall, 1994
 Mean: 60.25 Std Dev.: 5.51

ITEM ANALYSIS BY PERCENTAGE

	A	B	C	D	E	Invalid
1.	0.6	69.8	21.5	5.8	2.3	0
2.	10.5	7	11	9.3	62.2	0
3.	18	11.6	7	20.9	42.4	0
4.	8.7	4.7	15.1	70.9	0.6	0
5.	59.9	3.5	11.6	23.8	1.2	0
6.	8.7	4.7	74.4	1.2	11	0
7.	0	21.5	69.8	8.7	0	0
8.	69.2	12.2	9.3	4.7	4.1	0.6
9.	0.6	2.9	1.2	1.7	93.6	0
10.	8.7	75	1.7	9.3	5.2	0
11.	2.3	4.1	3.5	89.5	0.6	0
12.	1.7	97.1	0	1.2	0	0
13.	24.4	30.8	34.3	4.1	6.4	0
14.	5.2	89.5	1.2	2.9	1.2	0
15.	20.9	33.1	34.3	8.7	2.3	0.6
16.	11	18	58.1	3.5	9.3	0
17.	8.7	7.6	23.8	20.3	39.5	0
18.	10.5	39	27.3	19.2	3.5	0.6
19.	11.6	26.7	54.7	2.9	4.1	0
20.	37.2	36.6	18.6	5.2	2.3	0

EXAMINATION NAME: FINAL CONTINUED

21.	70.3	9.3	1.2	8.7	10.5	0
22.	7	12.2	5.2	11.6	64	0
23.	4.1	28.5	5.8	59.3	2.3	0
24.	22.1	19.2	7.6	7	44.2	0
25.	5.8	0.6	89	2.9	1.7	0
26.	16.9	27.3	5.8	41.9	8.1	0
27.	0	83.1	6.4	6.4	4.1	0
28.	3.5	10.5	4.7	64.5	16.9	0
29.	15.1	12.8	58.7	7.6	5.8	0
30.	7	81.4	9.3	2.3	0	0
31.	22.7	1.7	7.6	65.7	2.3	0
32.	4.1	14.5	18.6	43.6	19.2	0
33.	18	16.9	43.6	21.5	0	0
34.	8.1	9.3	13.4	15.1	53.5	0.6
35.	57	11	8.1	15.1	7.6	1.2

APPENDIX M

ENROLLMENT

Chemistry 1202 Enrollment Spring/1992 - Fall/1994

Spring 1992 - 2s/92

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Williams	211	177
2.	Williams	224	197
3.	Reed	212	175
4.	Reed	218	177
5.	Reed	169	140

Summer 1992 - 3s/92

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Johnson	127	97

Fall 1992 - 1s/93

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Henry	204	227
2.	Reed	92	89
3.	Reed	203	177

Spring 1993 - 2s/93

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Collins	230	194
2.	Taylor	230	189
3.	Wallace	191	135
4.	Reed	230	204
5.	Reed	192	150
6.	Hoffman	75	24

Summer 1993 - 3s/93

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Johnson	113	84

Fall 1993 - 1s/94

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Taylor	204	165
2.	Henry	227	229
3.	Reed	196	193

Spring 1994 - 2s/94

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Wallace	225	194
2.	Martin	222	201
3.	Reed	156	127
4.	Reed	219	211
5.	Reed	219	177
6.	Hoffman	78	22

Summer 1994 - 3s/94

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Johnson	108	107

Fall 1994 - 1s/95

<u>Section</u>	<u>Instructor</u>	<u>Initial Enrollment</u>	<u>Final Enrollment</u>
1.	Strahler	187	145
2.	Henry	220	202
3.	Reed	204	178

APPENDIX N

ANCOVA SOURCE TABLE FOR PRE-POSTTEST

Dep Var: postt N: 52 Multiple R: 0.257 Squared multiple R: 0.057

Analysis of Variance					
Source	Sum-of-squares	DF	Mean-square	F-ratio	P
Group	50.941	1	50.941	0.494	0.486
Pret	241.913	1	241.913	2.346	0.134
Error	4022.373	39	103.138		

Dep Var: postc N: 52 Multiple R: 0.306 Squared multiple R: 0.094

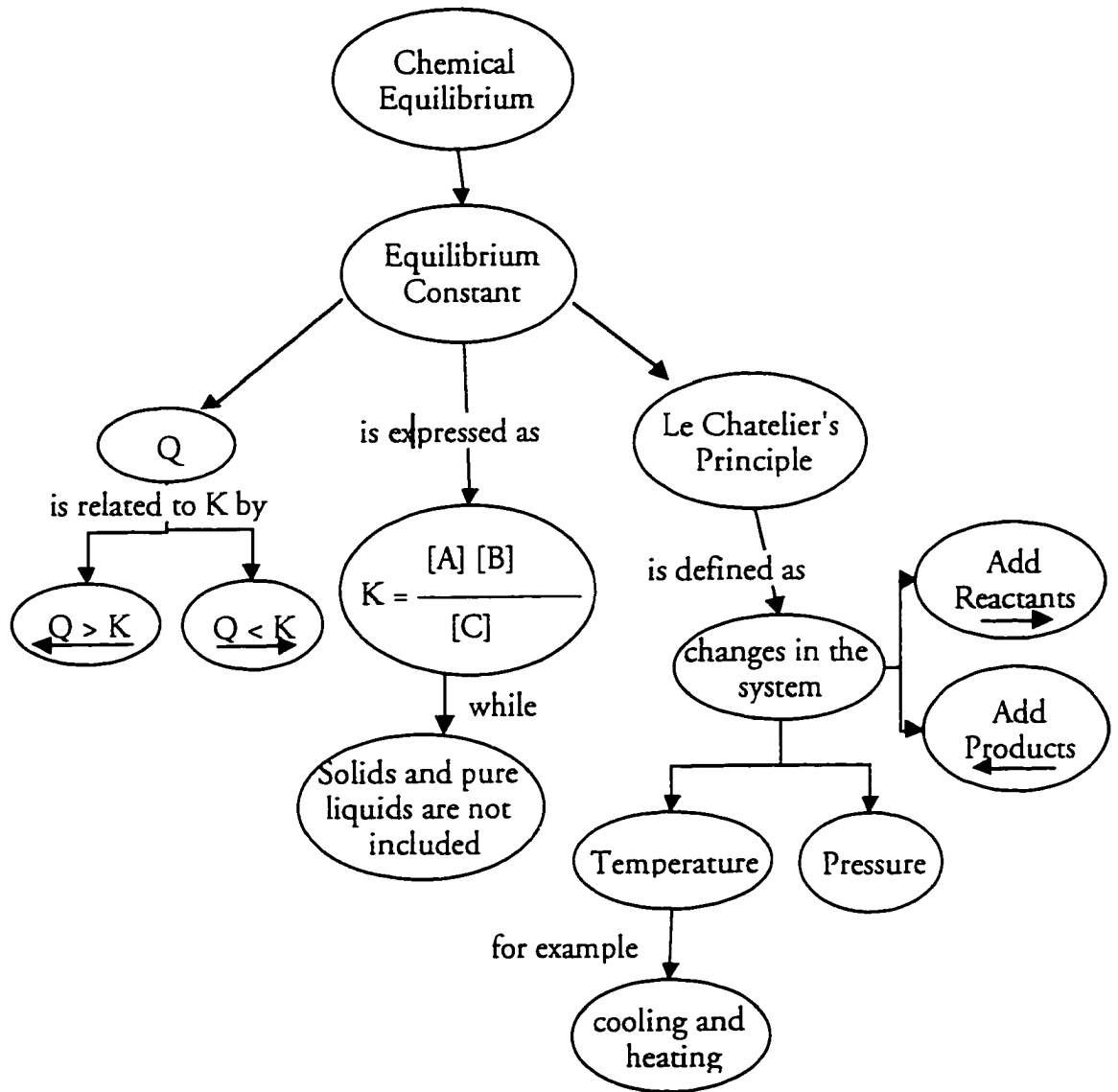
Analysis of Variance					
Source	Sum-of-squares	DF	Mean-square	F-ratio	P
Group	62.599	1	62.599	1.725	0.197
Prec	88.198	1	88.198	2.43	0.127
Error	1415.373	39	36.292		

Dep Var: postq N: 52 Multiple R: 0.240 Squared multiple R: 0.094

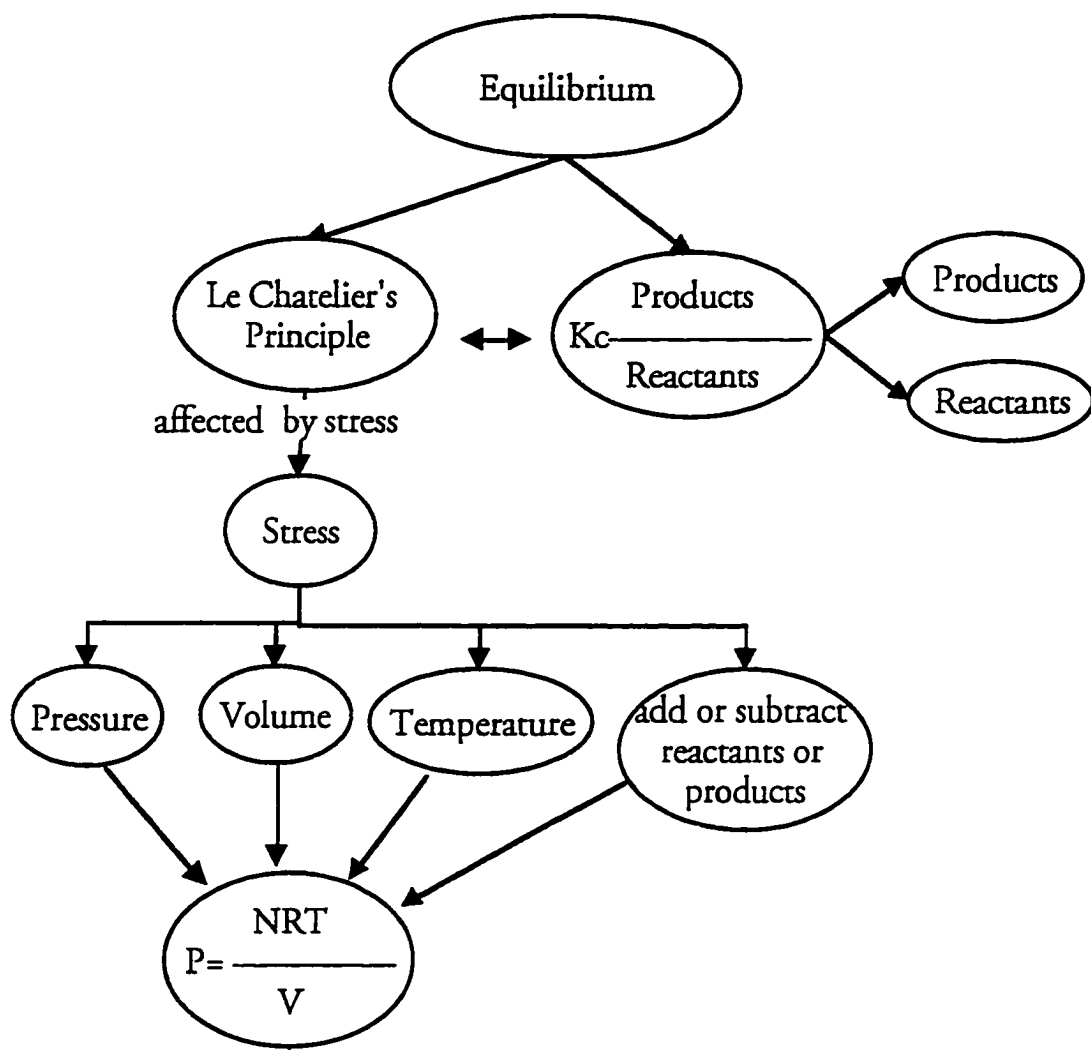
Analysis of Variance					
Source	Sum-of-squares	DF	Mean-square	F-ratio	P
Group	0.125	1	0.125	0.002	0.968
Preq	185.453	1	185.453	2.377	0.131
Error	3043.118	39	78.029		

APPENDIX O

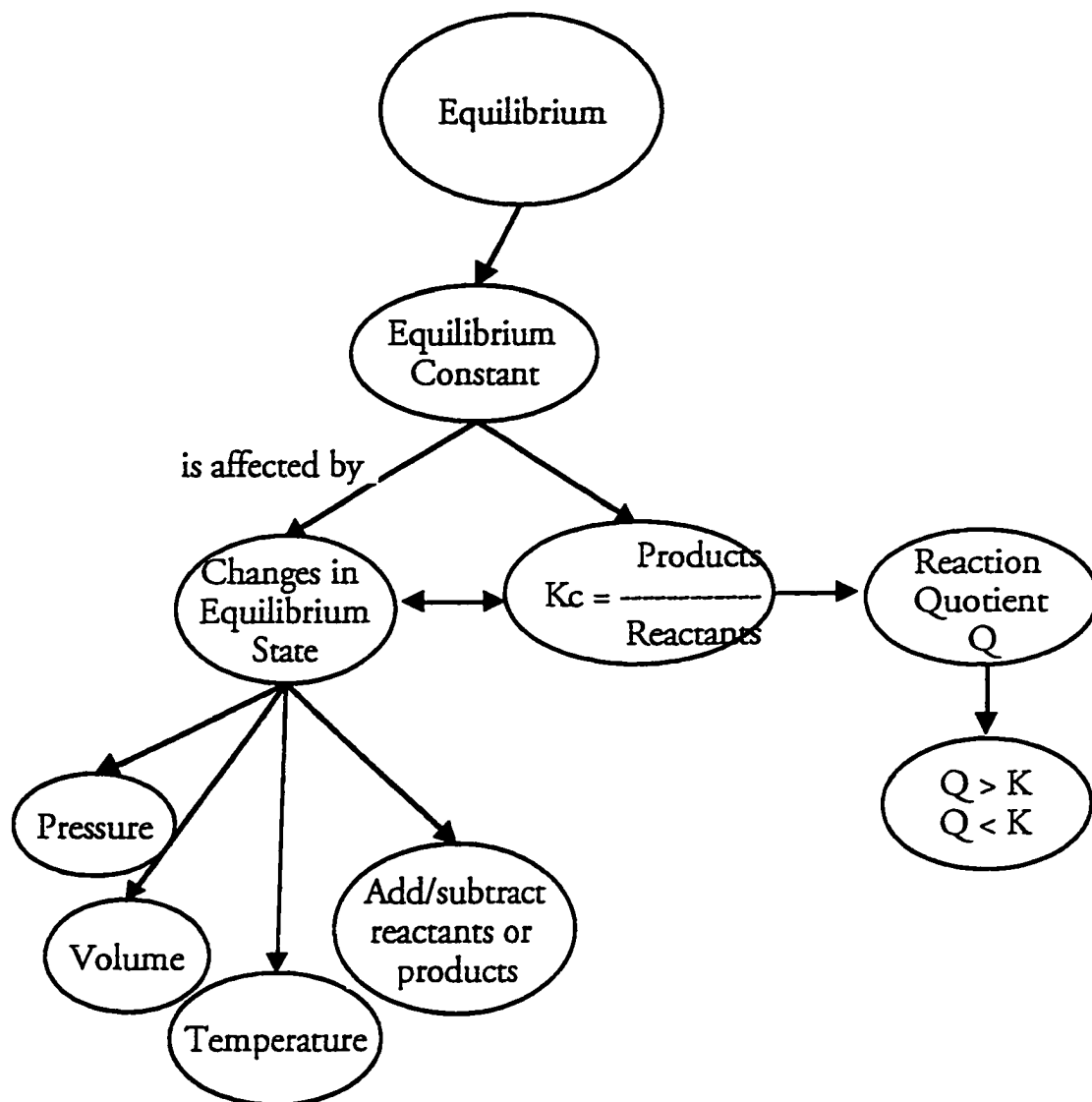
PARTICIPANT CONCEPT MAPS



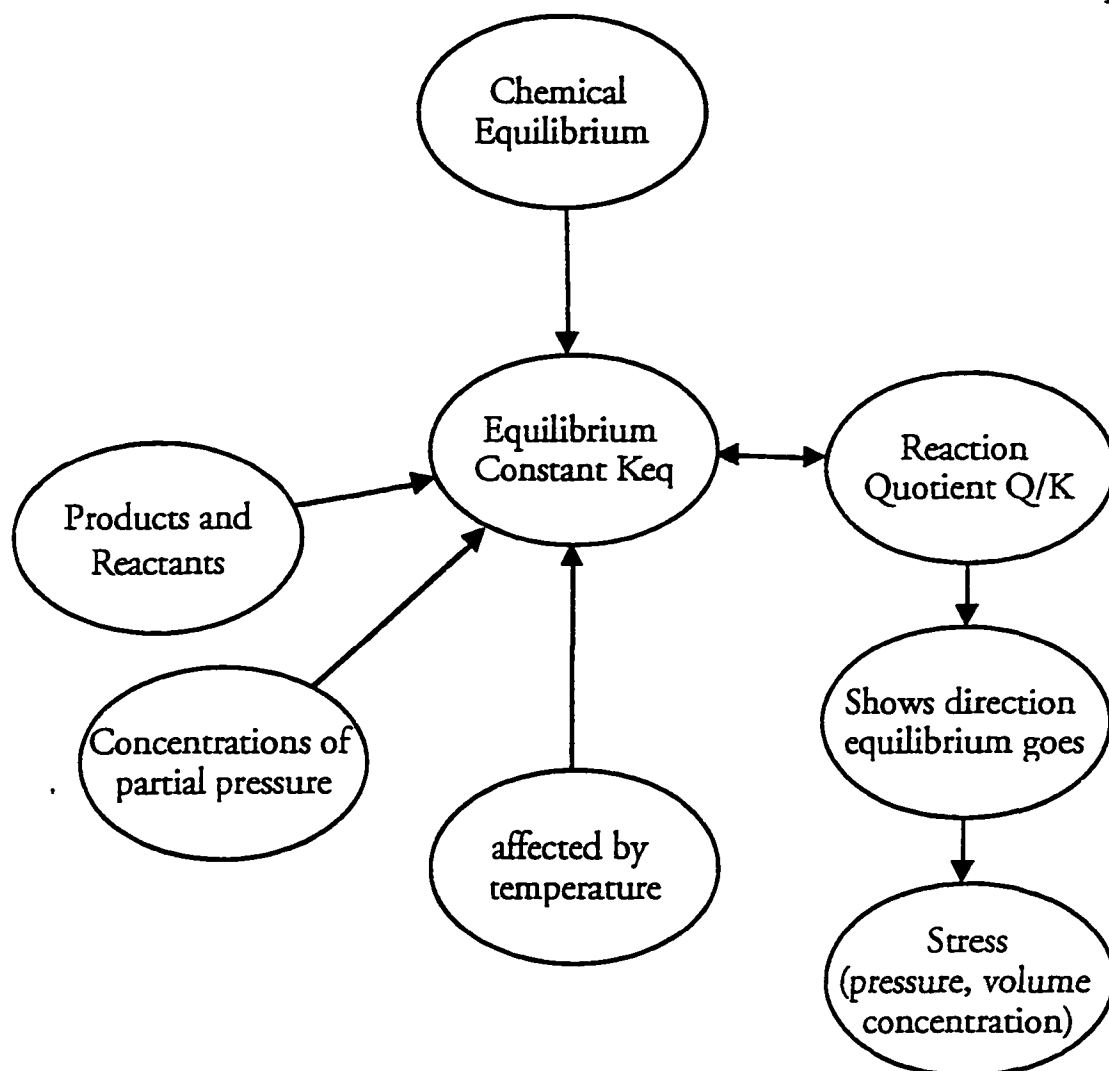
Michelle



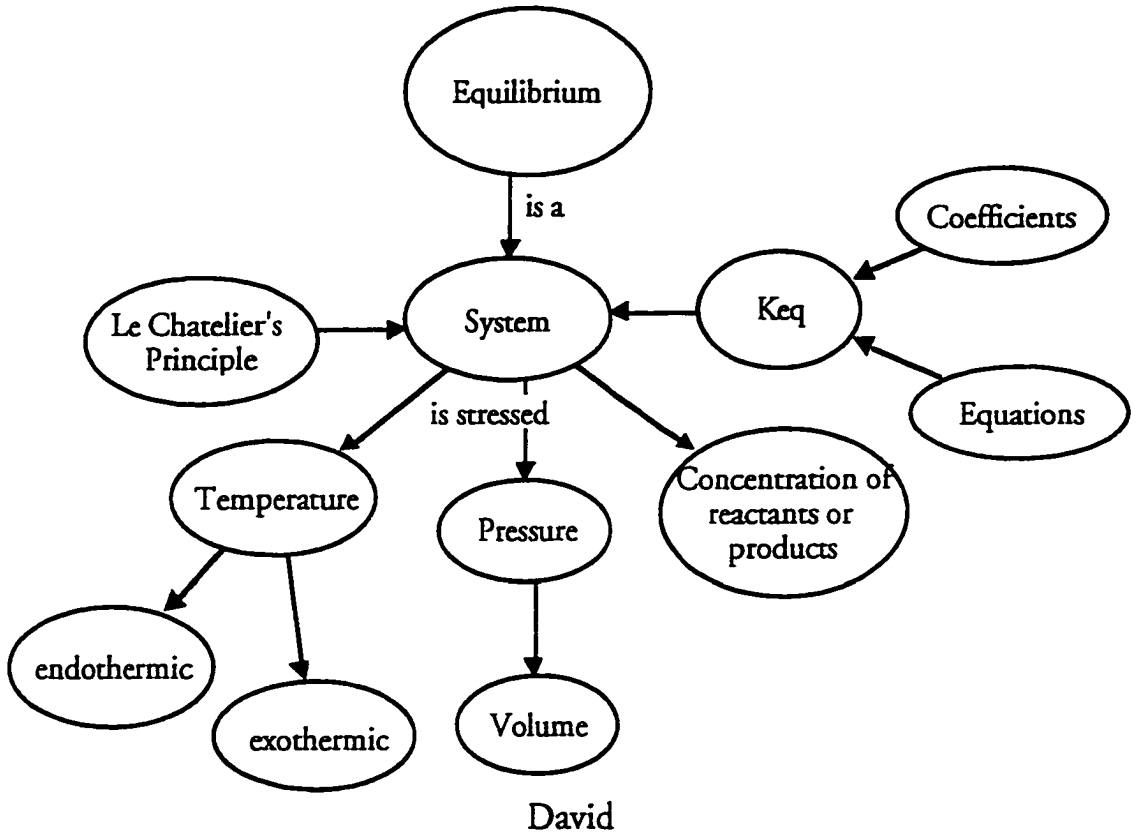
Gary

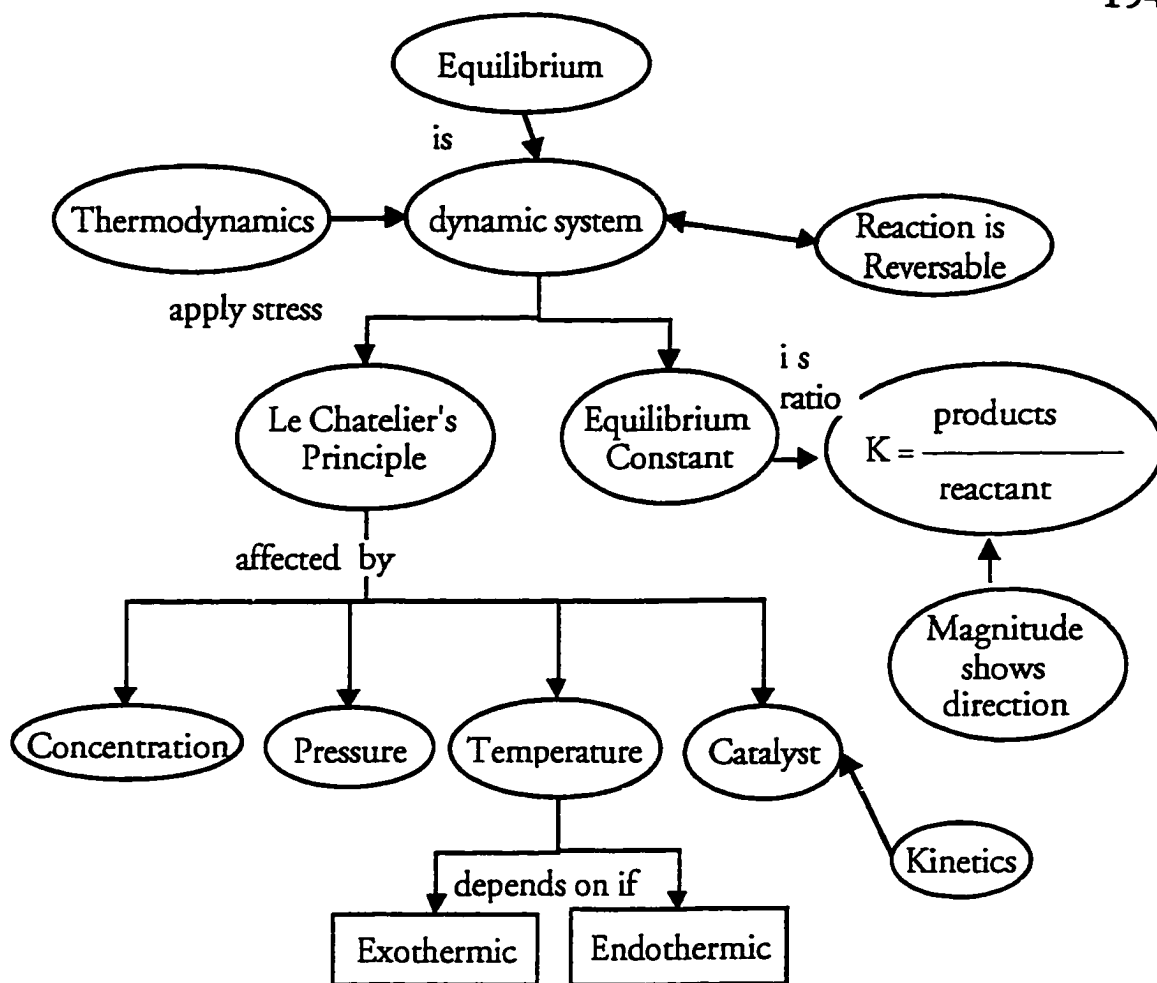


Scott

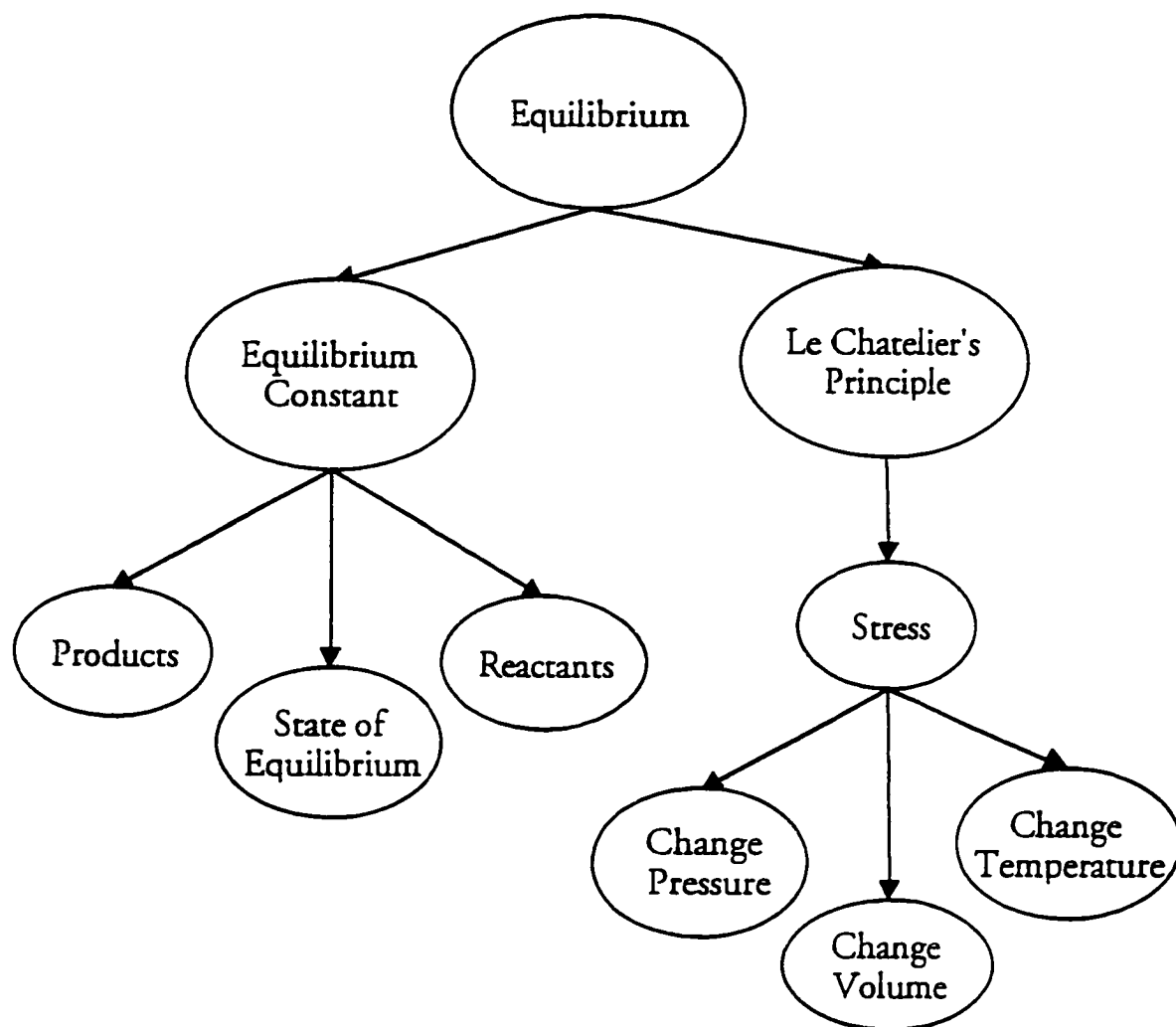


Richard

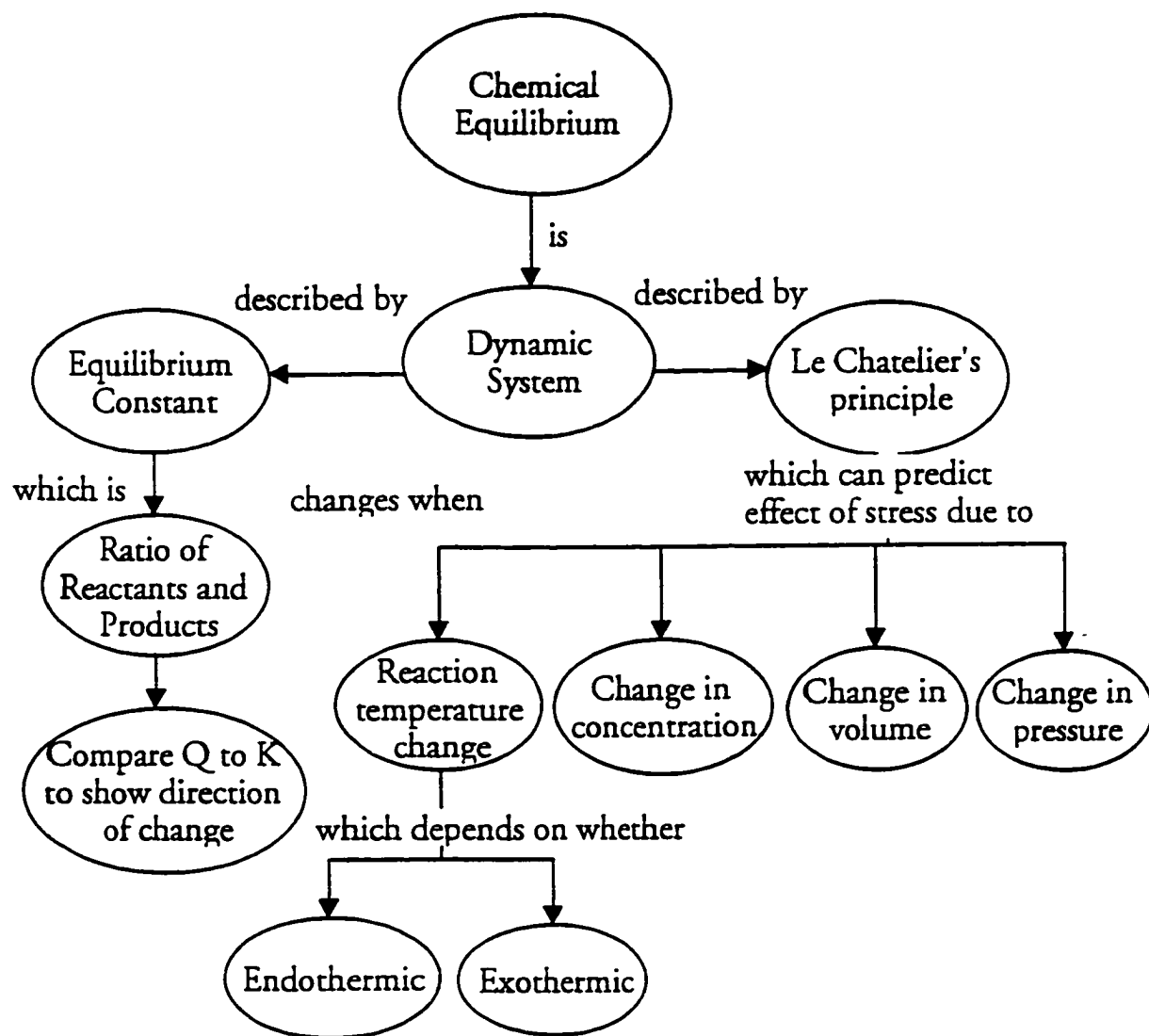




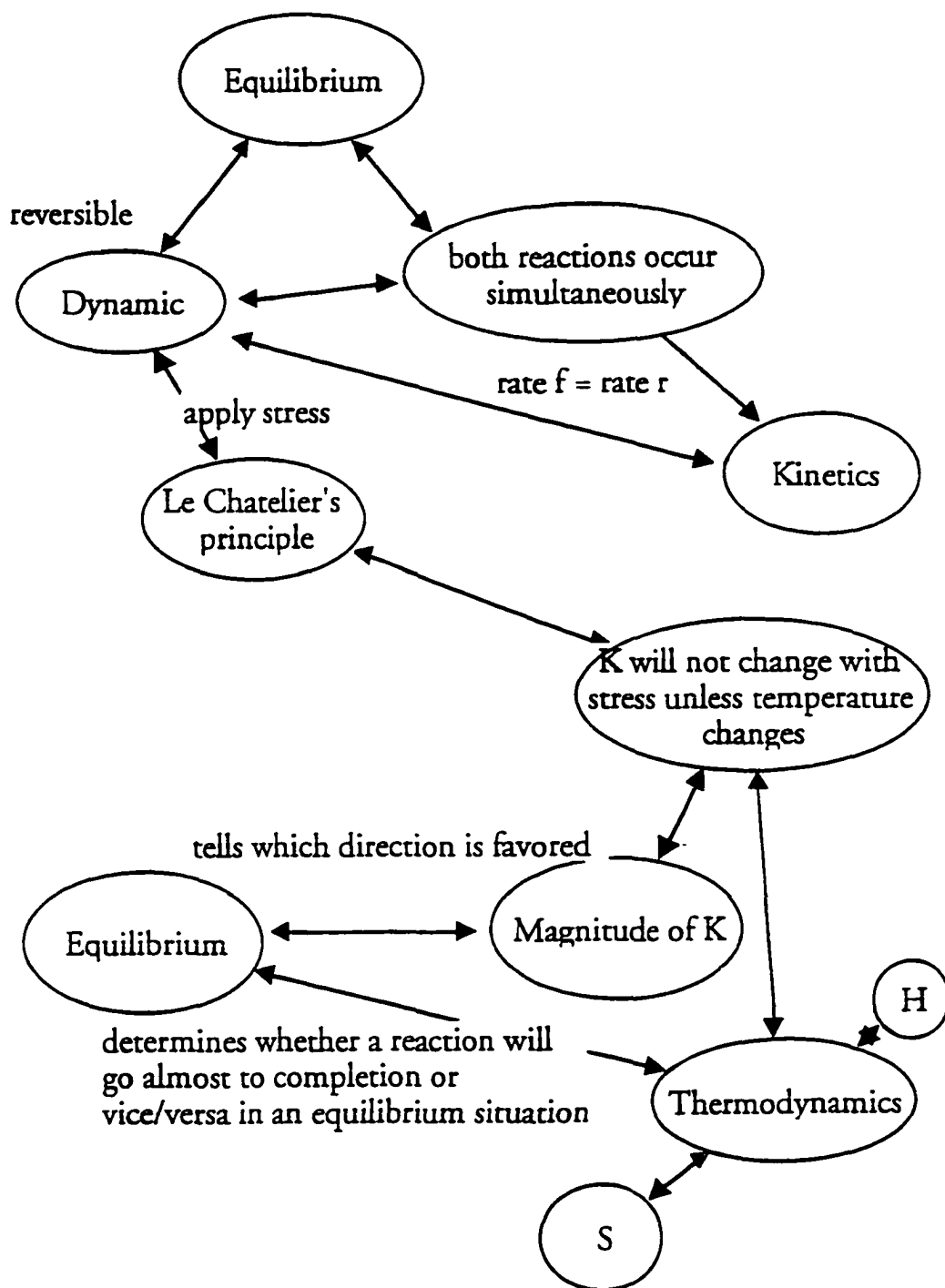
Derek



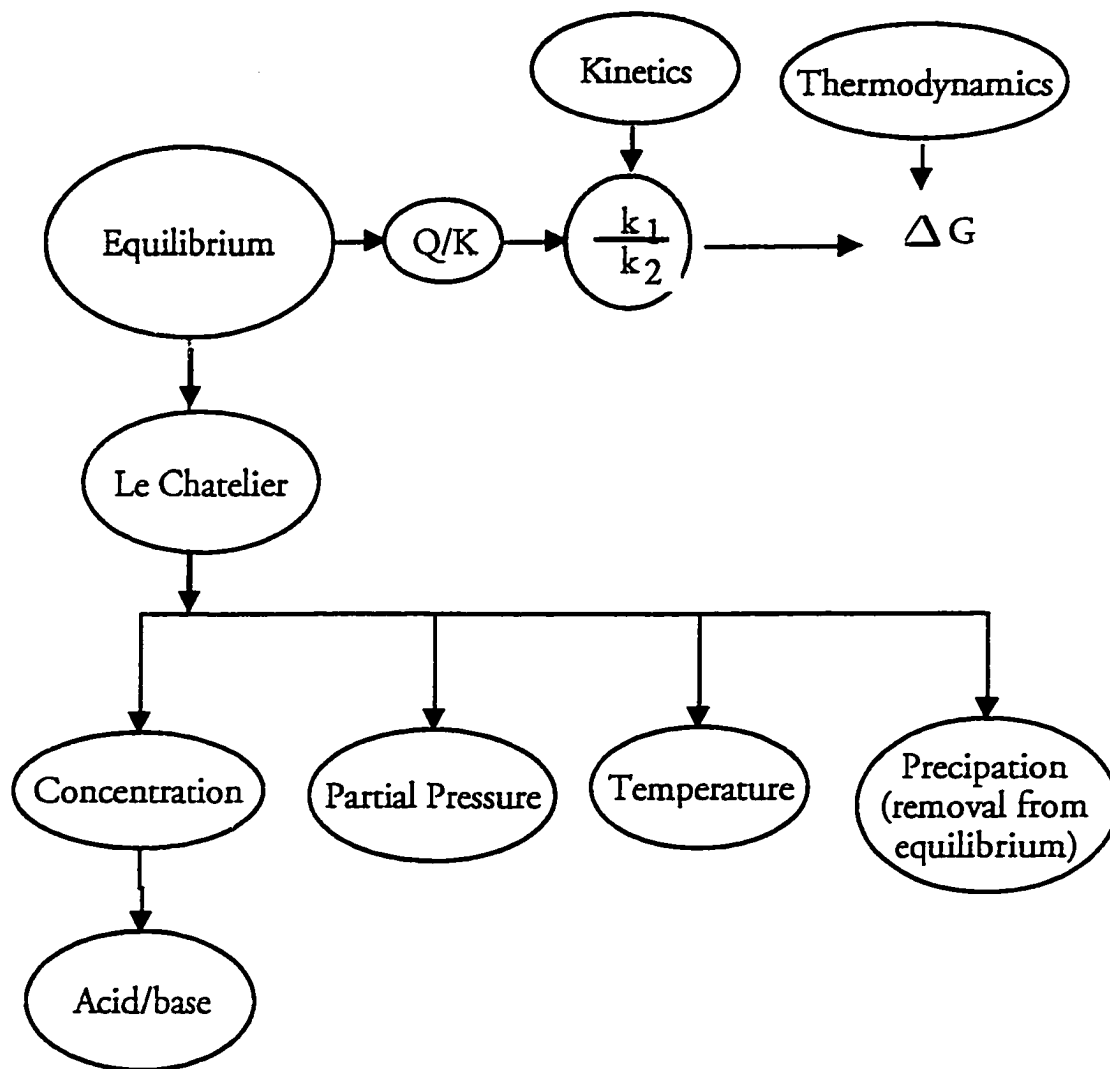
Grace



Frank



Conceptual Teacher



Traditional Teacher

VITA

Charles J. Killebrew is a student in the Department of Curriculum and Instruction at Louisiana State University. His academic background includes course work in biology and chemistry and he holds both bachelor of science and master of science degrees in biology from Southeastern Louisiana University.

Charles has served as an Assistant Marine Biologist with the research and teaching staff of the Gulf Coast Research Laboratory in Ocean Springs, Mississippi. His master's thesis research, conducted in residence at the laboratory, involved experimental studies of the reproductive physiology of marine fishes and the physico-chemical requirements for development of early life stages.

While working with state government in Louisiana, Charles was appointed to the Governor's staff to help develop the state's Coastal Wetlands Restoration Initiative. He has chaired or served as a member of various environmental committees and commissions at both the state and national level and was recently appointed to the state Environmental Education Commission. Charles has authored or co-authored a number of publications in the area of environmental science and resource management. His academic affiliations include membership in the Louisiana State University Chapters of Phi Kappa Phi and Sigma Xi.

Charles is currently a candidate for the doctor of philosophy degree in Curriculum and Instruction in the College of Education at Louisiana State University; this degree will be conferred in December, 1997.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Charles J. Killebrew

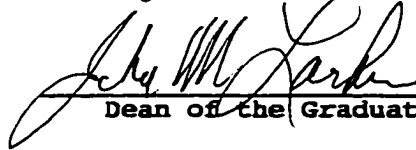
Major Field: Curriculum and Instruction

Title of Dissertation: Teacher Conceptions and the Curriculum: A Longitudinal, Multicase Study of College Chemistry Teaching

Approved:

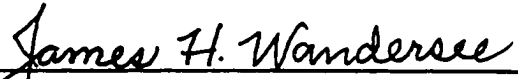


Major Professor and Chairman



Dean of the Graduate School

EXAMINING COMMITTEE:





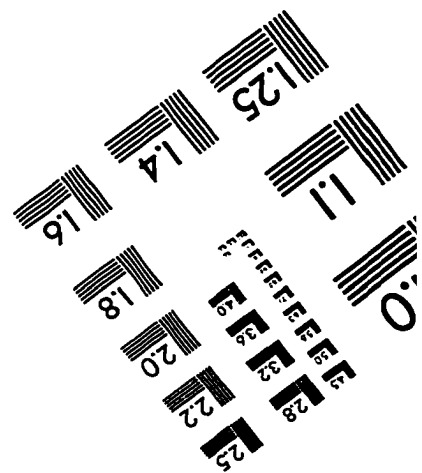
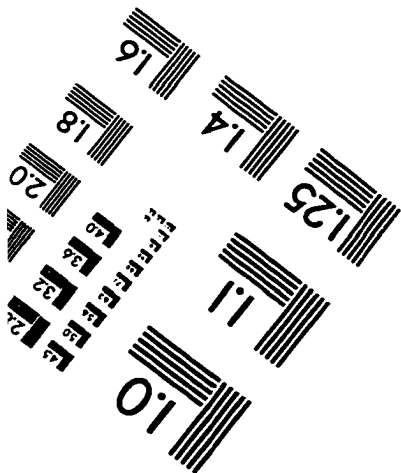
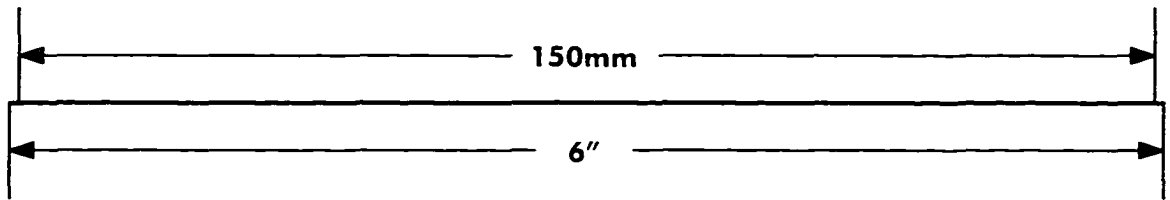
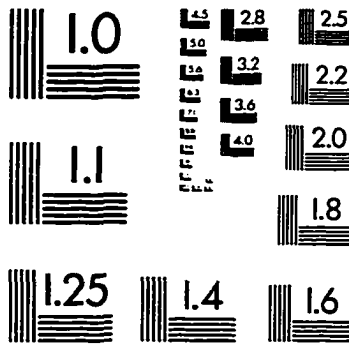
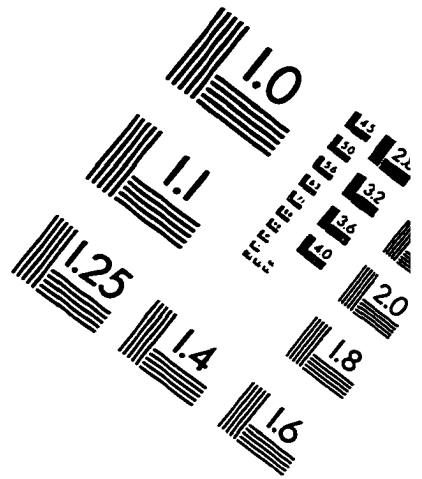
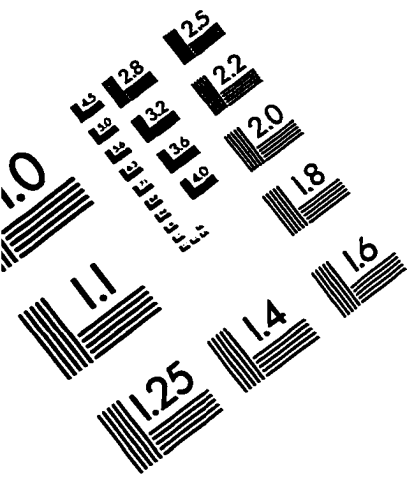




Date of Examination:

August 22, 1997

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