# Concept Maps as a Tool To Assess Learning in Chemistry

Bradford D. Pendley[1] and Richard L. Bretz
Dpeartment of Chemistry, Baker Laboratory, Cornell University, Ithaca, NY 14853

Joseph D. Novak[2]
Department of Education, 421 Kennedy Hall, Cornell University, Ithaca, NY 14853

A common experience of chemistry teachers is that students may do well on examination questions, yet fail to acquire skill in solving even routine textbook problems. In the past decade, there has been a considerable body of research that has illustrated the common problems students have in acquiring an understanding of chemistry concepts and principles (*1–15*). We believe the major factors underlying the problems commonly observed are

(1) students are learning predominantly by rote, rather than actively seeking to construct their own meanings for the subject matter;
(2) the chemistry subject matter remains largely "conceptually opaque" to students, and they do not recognize the key concepts nor concept relationships needed to understand the subject matter; and
(3) the instruction may fail to present these key concepts or concept relationships and thus remains "conceptually opaque" to the students.

For more than 75 years, the dominant views regarding learning came from the laboratories of behavioral psychologists. The epitome of this work is illustrated by B. F. Skinner's *The Behavior of Organisms* (*16*). Applied to school learning, behavioral psychology eschewed more qualitative studies, such as those carried on by Piaget in Geneva and by his followers in other countries. Piaget's monumental works, as well as other psychological studies focusing on understandings constructed by learners, began to be recognized in this country in the 1960's. Currently, cognitive psychology dealing with how students construct and use meanings about how the world works is overwhelmingly dominant (*17–19*). Piaget's work, made familiar to many readers of *this Journal* by Herron (*20–22*) and his colleagues, still remains important to understanding children's learning, but the current views are that the limited success of students in learning and problem solving reflects more the lack of well-organized conceptual frameworks than limitations in their brain functioning due to restricted "cognitive operations" (*23–24*). Our studies strongly support the central role that conceptual understanding plays in acquiring new knowledge in any domain and applying knowledge in novel problem-solving settings (*25–28*).

To develop well-organized conceptual frameworks requires a commitment on the part of the student to choose to learn *meaningfully* rather than by rote. Meaningful learning requires the learner to seek explicit conceptual linkages between relevant knowledge he/she already has and new knowledge being presented (*29*). The unfortunate situation is that so much of school learning from grade one onward requires little more than verbatim memorization of concept definitions or problem-solving algorithms.

Concept maps were developed to represent changes in students' knowledge structures over time (*30*). They are based on the epistemological idea that concepts and concept relationships (i.e., propositions) are the building blocks of knowledge. Furthermore, hierarchical structures of concepts and propositions are convenient and concise representations of knowledge. In this paper, we report on the use of concept maps drawn from clinical interviews, as tools to assess learning in two groups of chemistry students.

The first study was done with students enrolled in a sophomore-level physical/analytical chemistry course, while the second involved first-year PhD students at Cor-

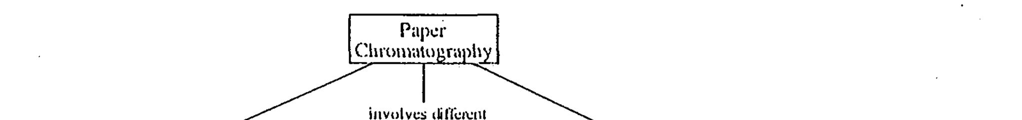


Figure 1. Pre-instructional concept map for student #4, study 1.

[1]Present address: Department of Chemistry, Rhodes College, Memphis, TN 38112.
[2]Author to whom correspondence should be addressed.

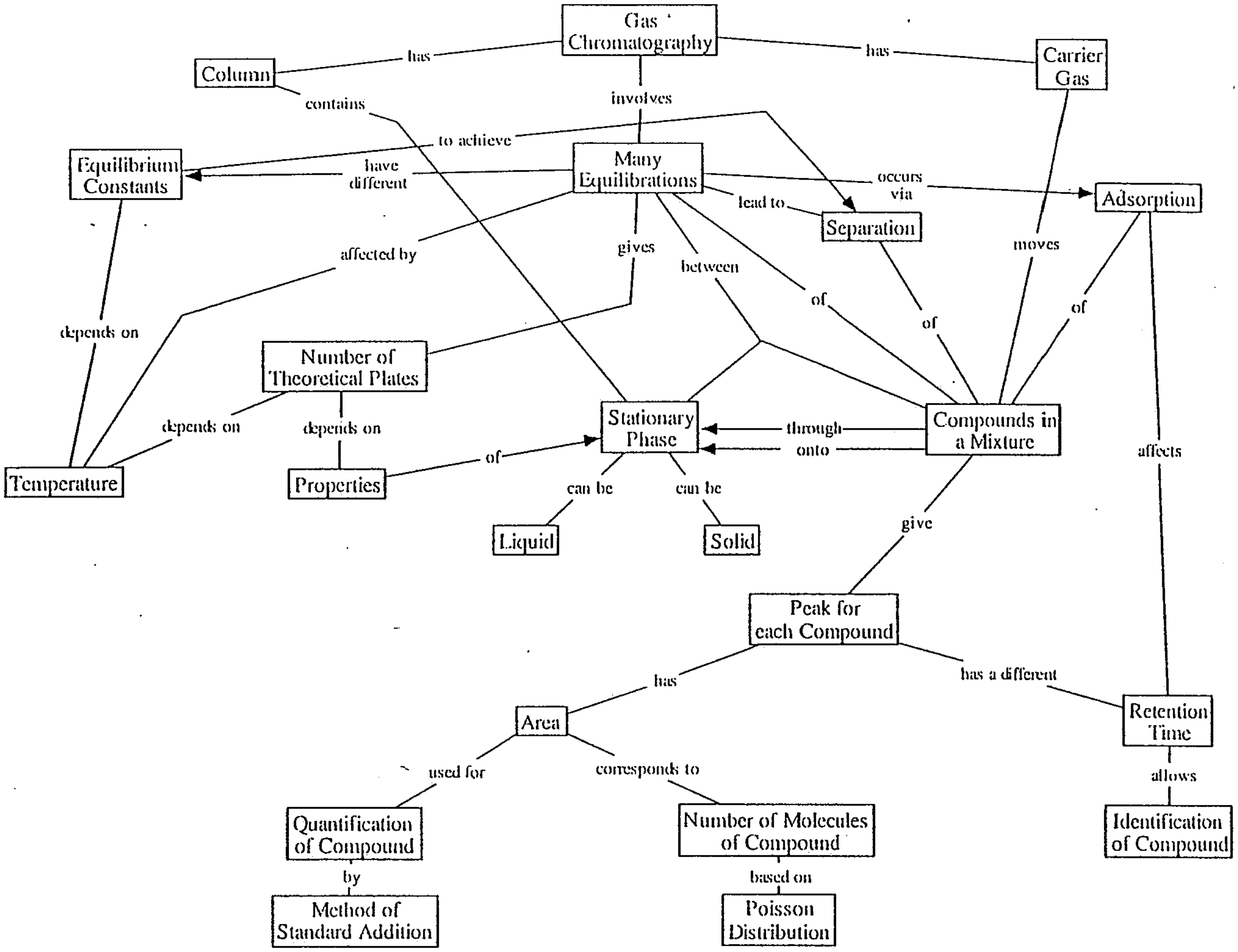


Figure 2. Post-instructional concept map for student #4, study 1.

nell University. Both studies focused on the use of concept maps to illustrate and assess the students' understanding of the concepts related to their learning of chromatography.

## Method of Research

The clinical interview was developed by Piaget as a technique to probe the cognitive structure (mental organization) of individuals. We have modified Piaget's methods to probe the explicit conceptual/propositional frameworks held by subjects as a means to understand what "meaning frameworks" they bring to new learning tasks, or what they possess after learning tasks. Our approach is to prepare a *concept map* to represent the knowledge organization in the subject matter domain of concern.

### *Study One*

Six students, two women and four men, volunteered to participate in the study. The students were *not* representative of the class. They were all above average (i.e., A) students in the course. The students were enrolled in a sophomore-level, physical/analytical chemistry lecture/laboratory course for chemical engineers at Cornell University. All six students had at least one year of high school chemistry (five had two years), one year of general chemistry, a semester of physical chemistry lecture, and a semester of physical/analytical chemistry lecture/laboratory. They currently were enrolled in the second semester of physical chemistry lecture. Five of the students previously had done a paper chromatography experiment in high school or college.

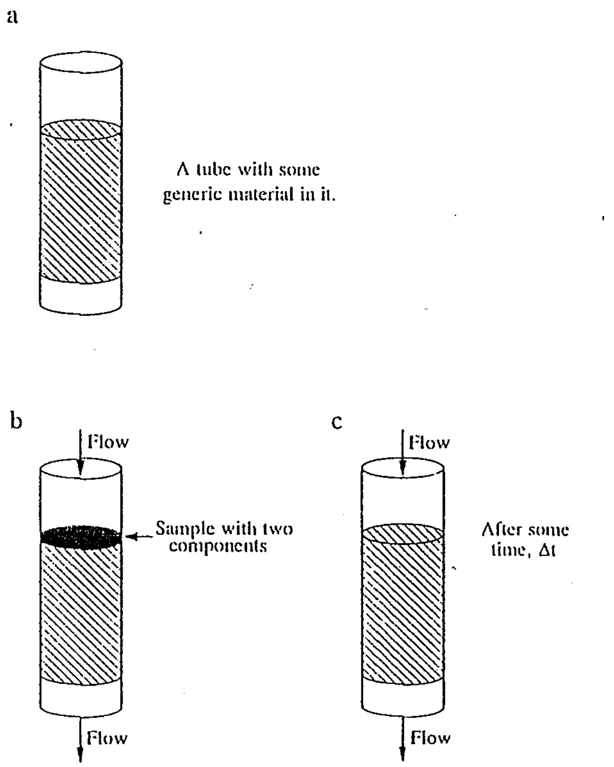


Figure 3. Visual aid used during pre- and post-instructional interviews. Student was asked to sketch in part c, using different color markers, how the separation would look after some time, $\Delta t$.

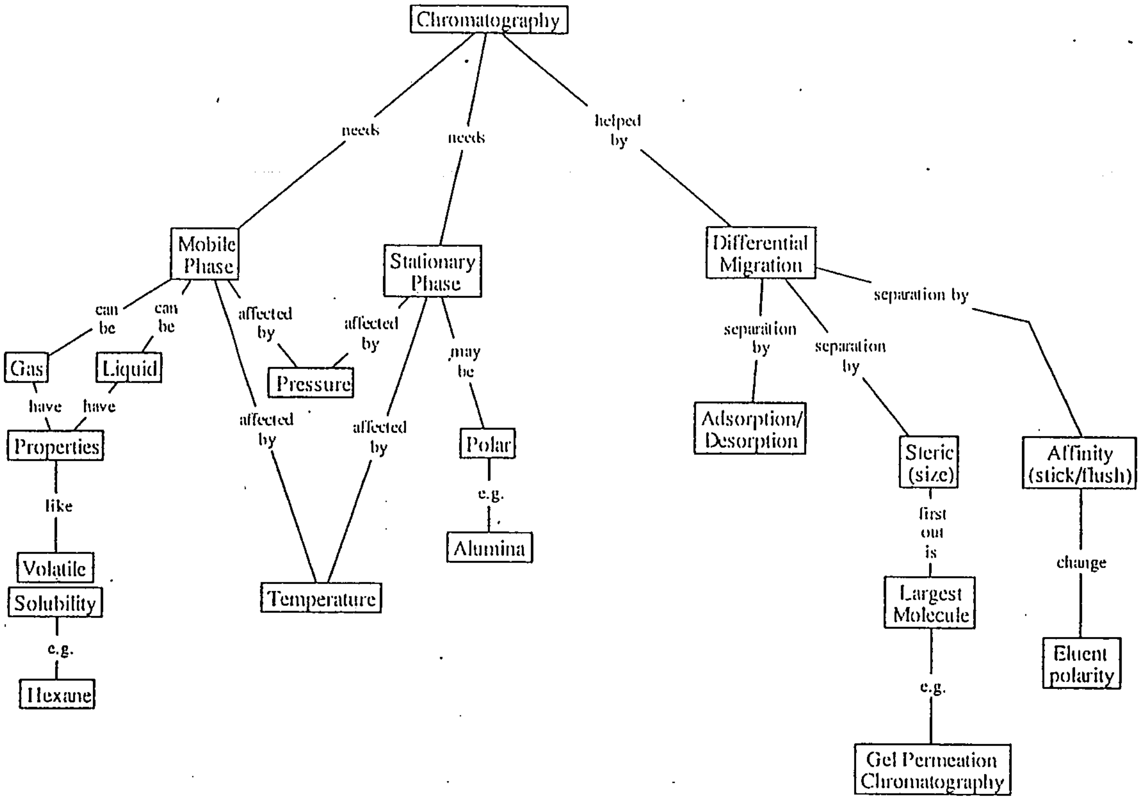


Figure 4. Pre-instructional concept map for student #1, study 2.

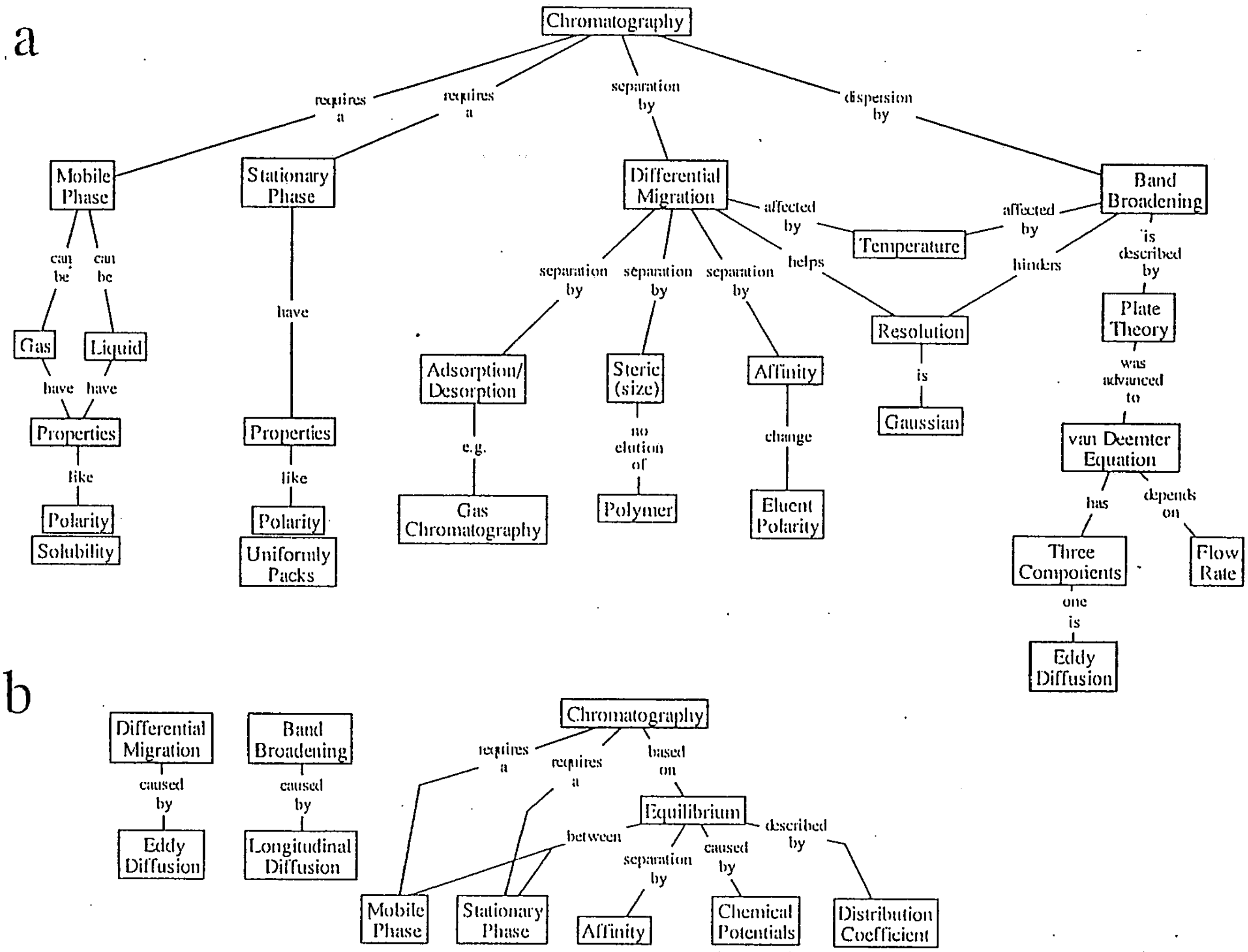


Figure 5. Pre-instructional concept map (a) and examination answers in concept map form (b) for student #4, study 2.

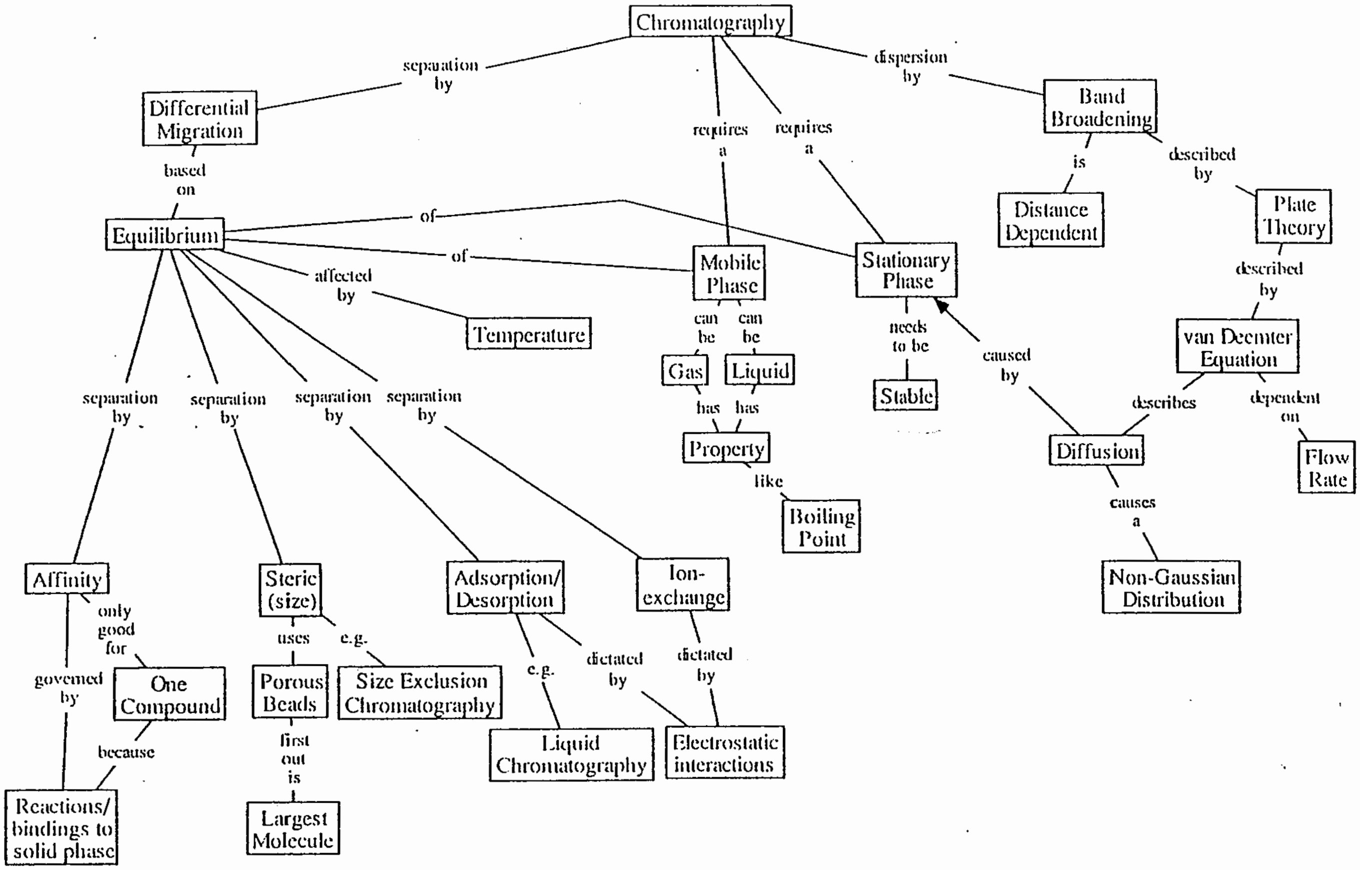


Figure 6. Post-instructional concept map for student #1, study 2.

Prior to any instruction about chromatography in the course, each student was interviewed to ascertain his/her knowledge of chromatography (in all cases, paper chromatography). The post-instructional interviews focused on concepts related to gas chromatography and were done two weeks after the completion of the last laboratory exercise in chromatography. None of the students prepared for either interview.

Each interview lasted between 20–30 min and was recorded on audiotape. From the audiotape of each interview, notes were taken and concept maps were prepared. Representative maps are shown in Figures 1 and 2. At the

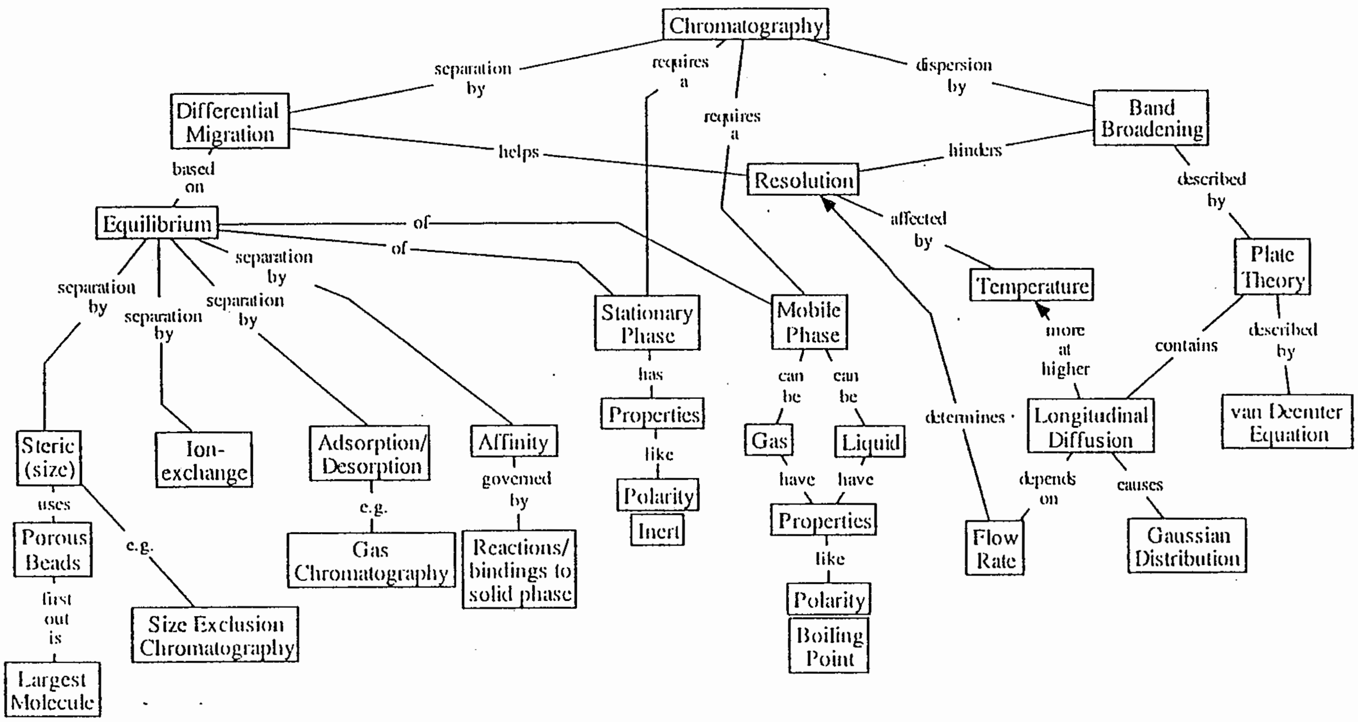


Figure 7. Post-instructional concept map for student #4, study 2.

completion of the course, the students were given numerical problems related to chromatography (e. g., resolution and theoretical plate calculations) as part of their final examination.

### Study Two

Five students (one woman and four men) volunteered to participate in the study. The students represented the fields of analytical, physical, and inorganic chemistry in addition to materials science. All five students were first-year graduate students at Cornell University who had not demonstrated competency on the American Chemical Society Graduate Analytical Chemistry Examination and were, therefore, attending a series of lectures designed to review fundamental concepts in analytical chemistry. At a minimum, all of the students had been exposed to both column and gas chromatography as undergraduates.

Prior to any instruction on chromatography in the course, each student was interviewed to ascertain his/her knowledge of chromatography. The students then attended weekly lectures for three weeks followed six weeks later by a written examination. Since studies have shown that most information learned by rote is lost within six to eight weeks (*31*), the post-instructional interview was conducted 14 weeks after the last chromatography lecture. None of the students prepared for either interview. Unintentionally, two of the students were concurrently teaching assistants for a junior-level physical/analytical chemistry laboratory course where chromatography was covered prior to the pre-instructional interview.

A visual aid (Fig. 3) was developed and revised on the basis of three pilot interviews to help elicit pertinent responses from the students without asking questions that could lead them into correct responses. During the interview, the student was asked how the sample would look after some period of time. Using a red and a green marker to represent the two different components of the sample, the student sketched his/her answer in Figure 3c. In this way, the student was able to demonstrate his/her knowledge of differential migration and band broadening. Particular questions were then based on the details of the sketch in order to develop a concept map for the student.

Each interview lasted between 20–40 min and was recorded on audiotape. From the audiotape and the visual aid, a concept map was constructed for each interview. Representative maps are shown in Figures 4–7. Partial concept maps were constructed based on the answers given to two questions on the course's cumulative final examination.

## Nature of the Instruction

### Study One

Instruction on the concepts, principles, and theory of gas chromatography was provided during three 50-min lectures and three three-hour laboratory periods. The first lecture described separation occurring via the partitioning of solute between the stationary and mobile phases, related the partition coefficient to Raoult's law, and discussed Plate Theory for elution chromatography. The second lecture discussed resolution, Rate Theory, and the van Deemter equation, while the third lecture focused on column-packing materials, deviations from Raoult's law and their effects on peak shape, and the method of standard addition. The first day of laboratory instruction involved an exercise designed to study the relationship between temperature and the number of theoretical plates and required the identification of selected compounds in a gasoline sample on the basis of their retention times. The second and third laboratory periods were spent analyzing gasoline samples for toluene using the method of standard addition.

### Study Two

Instruction on the concepts, principles, and theory of chromatography was provided during three 60-min lectures. Prior to planning the instruction, the lecturer (first author) had constructed a concept map on chromatography to serve as a guide for preparing the lectures. The lectures were audiotaped by the second author, who then generated a concept map against which to compare the student's maps.

The first lecture centered on the difference between differential migration and band broadening. The second lecture discussed mechanisms of differential migration by distinguishing between equilibrium and nonequilibrium methods of separation. A discussion of the chemical parameters (i. e., retention time, capacity factor, and selectivity factor) and their control also was included in the second lecture. The third lecture dealt with band broadening from the view of both Plate Theory and the more advanced Rate Theory, as well as the effects differential migration and band broadening have on resolution.

## Results and Discussion

### Study One

Figure 1 shows a concept map constructed from a pre-instructional interview with one student (Student #4), which illustrates this student's understanding of differential migration (although a mechanism is not known), the identification of substances based on distance traveled, the idea that the separated compounds were present as distinct regions (possibly giving some indication of band broadening) and that the solution is present but plays some unknown role. In addition to this student, two more students (Students #5 and #6) similarly demonstrated some understanding of the concepts and principles involved in paper chromatography. In all three cases, the principle of differ-

**Table 1. Major Concepts Held by Students In Study 1 Prior to Instruction on Chromatography**

| Student | Basis of Separation | Role of Mobile Phase | Identification of Compound Based on | Band Broadening |
|---|---|---|---|---|
| 1 | No prior experience with chromatography | | | |
| 2 | different properties of paper and compounds | no solvent | unknown | unknown |
| 3 | unknown | unknown | unknown | unknown |
| 4 | different rates of molecular movement | solvent present | distance compound travels on paper | "distinct regions" |
| 5 | different amounts of solubility of compound in solvent | solvent carries compounds | distance compound travels on paper | "bands" |
| 6 | different rates of molecular movement | molecules move in solvent | distance compound travels on paper | unknown |

Table 2. Major Concepts Held by and Test Results of Students in Study 1 after Instruction on Gas Chromatography

| Student | Basis of Separation | Mechanism | Role of Mobile Phase | Identification of Compounds | Limitations to Separation | Test Score |
|---|---|---|---|---|---|---|
| 1 | different rates of molecular movement | diffusion | moves sample through column | retention time | none | 11/15 |
| 2 | different rates of diffusion | diffusion | no mobile phase | "peak time" | none | 15/15 |
| 3 | different rates of diffusion | diffusion | none | retention time | none | 15/15 |
| 4 | equilibration of compounds with stationary phase | adsorption | moves sample through stationary phase | retention time | none | 15/15 |
| 5 | different velocities of compounds traveling through stationary phase | equilibrium process | moves sample through stationary phase | retention time | none | 15/15 |
| 6 | different velocities of compounds traveling through solid phase | Graham's law of diffusion; electrostatic interactions; kinetic energy of compounds | moves sample through stationary phase | "peak time" | none | 9/15 |

ential migration was present (although a specific mechanism was unknown), and the identification of components in a mixture based on the distance traveled by a component was clearly defined. Two of the three students saw the solvent as the phase in which the molecules traveled, and two described the separated compounds as bands or broadened regions, but neither knew why this occurred. Table 1 summarizes the results of the pre-instructional interviews.

Figure 2 shows a concept map constructed from the post-instructional interview with student #4. From the student's pre-instructional map (Fig. 1), it was clear that the student understood the principle of differential migration. After instruction on gas chromatography, this principle showed significant growth and refinement as the student assimilated new concepts associated with differential migration.

The results derived from concept maps constructed from the post-instructional interviews with all students are shown in Table 2. Several observations were made. First, none of the six students had an understanding of the fundamental concepts related to band broadening and resolution. Although many students related the number of theoretical plates to the separation process through temperature, the concept was not well understood or defined. Second, there was a range in the level of understanding of the principle of differential migration. Comparison of Tables 1 and 2 shows that those students who had no prior instruction in chromatography and those with prior instruction but incorrect assimilation of the concepts, constructed or built upon the misconceptions they had to link these new concepts. In contrast, those students who had some understanding of the principles involved in the separation in paper chromatography were able to assimilate, to varying degrees, additional concepts related to gas chromatography and further refine their understanding of chromatography in general.

These results also were compared with each student's performance on exam questions related to two of the concepts in chromatography. Two questions were asked: (1) What platage is required to give a relative peak width ($w/t_r$) of 0.50 (5.0%)? (2) On the above column, two similar compounds gave retention times of 1200 s and 1300 s. What is the resolution for this analysis? The results (shown in Table 2) indicate that a student's performance on these questions did not accurately reflect the student's understanding of the concepts.

### *Study Two*

As can be seen in the representative pre-instructional concept maps (Figs. 4 and 5a), the first-year graduate students had a more complex cognitive framework on which to build during the instruction in chromatography than the students in the sophomore course. As seen in Figure 4, the concept of band broadening had not been incorporated into one student's conceptual framework of chromatography, even though the student had performed chromatography experiments in an undergraduate research laboratory. Of the four remaining students, two could describe the band broadening by the rudimentary Plate Theory; whereas, the two teaching assistants (Students #4 and #5) had advanced their understanding to the point of being able to describe some of the components of the van Deemter equation and its dependence on the flow rate of the mobile phase. Of the four students who had incorporated band broadening into their cognitive structure, only student #4 (Fig. 5a) described the distribution of molecules within the chromatographic separation band as being Gaussian.

Because studies have shown that numerical problem solving does not reflect a student's understanding of the concepts (*9–11*), the final examination questions were based on the explanation of chromatographic concepts. The two questions on chromatography were

(1) Briefly explain the concepts of differential migration (in general, not a specific mechanism) and dispersion (band broadening) and how each relate to separation in chromatography.
(2) Explain the partitioning mechanism in chromatography. In your discussion, show the relationships between partitioning, equilibrium, chemical potential, distribution coefficient, stationary phase, mobile phase, and the basis of separation.

The answers to these questions were then used to construct a partial concept map of the student's conceptual understanding. Even though the first question specifically asked for a relationship between differential migration and band broadening, only two students actually linked the two concepts. However, a comparison of Figures 5a, 7, and 5b illustrates how word questions can fail to reflect the students' conceptual understanding. The student showed the misconception of linking Eddy diffusion to differential migration on the exam, but during the pre- and post-instructional interviews, correctly linked diffusion concepts to Plate Theory.

Even though student #4 showed dramatic changes in conceptual framework, he/she was not alone in eliminating

and relinking concepts. During the post-instructional interviews, it was found that everyone but student #5 had eliminated all but one or two sub-concepts connected to the van Deemter equation. However, if the students had incorporated all of the concepts from the lectures into their conceptual framework, then they should have had five sub-concepts connected to the van Deemter equation. Conversely, it was found that all of the students had incorporated four of the five mechanisms of differential migration including its method of separation and examples into their conceptual framework. Unfortunately though, no one separated the mechanisms of differential migration into equilibrium and nonequilibrium processes, even after the instructor went into a long discussion as to why such a distinction is pertinent. However, some conceptual understanding did occur because four of the students, all of whom originally had misconceptions about the steric mechanism of differential migration (ex. Fig. 5), had corrected that misconception after instruction (ex. Fig. 7).

Mathematical expressions and terms (i. e., the van Deemter equation, chemical parameters, etc.) also did not do well in being learned meaningfully. Initially, only student #5 described the components of the van Deemter equation in mathematical terms. On the final examination, three students demonstrated mathematical knowledge. However, by the post-instructional interview, only one student (not student #5) could describe the mathematical relationships underlying the van Deemter equation.

Both teaching assistants in the undergraduate laboratory course initially had more conceptually complete concept maps with fewer misconceptions than the other students. This was to be expected given that the section on chromatography was taught one week prior to the pre-instructional interview. However, student #4 did not learn meaningfully either during the review course or while being a teaching assistant for the undergraduate course because during the pre-instructional interview (Fig. 5a), Eddy diffusion was linked correctly to the van Deemter equation, but on the final exam it was linked to differential migration (Fig. 5b). However, Eddy diffusion was excluded completely in the post-instructional interview (Fig. 7). In contrast to rote learning, meaningful learning requires a person to choose to relate his/her prior knowledge with new concepts and propositions in a substantive, non-arbitrary fashion. When this is done effectively, the student's knowledge structure is elaborated, and faulty understandings may be corrected through the integrative reconciliation of the prior concepts and propositions with the newly acquired concepts and propositions (*30*). The student also removed all sub-concepts of the van Deemter equation and relinked one of the former van Deemter sub-concepts directly to Plate Theory. Upon questioning, the student repeatedly failed to link diffusion to the van Deemter equation.

During the post-instructional interview, each student was asked how he/she prepared for the final examination. The students who took a more active role in learning (i. e., not just memorizing his/her lecture notes) showed a better integration of new concepts into his/her conceptual framework. However, not all of the misconceptions could be relinked to form valid conceptions.

## Conclusions

From these studies, several conclusions were drawn. First, regardless of how conceptually complete the material presented to the student is, the instruction alone does not convey understanding. The students must take an active role in the learning process by learning *meaningfully* rather than by rote. Secondly, these studies support the work by others (*9–11*) in that answering numerical problems correctly does not necessarily indicate or reflect a student's conceptual understanding of the material. We extended the problem-solving question to include questions requiring general, qualitative explanations. We found that most of the students' answers were indicative of essentially rote memorization of concepts and propositions, which rapidly became non-retrievable from memory, rather than answers that indicated meaningful learning and restructuring of concept/propositional knowledge in memory, which may be retrievable for months or years. Finally, we have shown that concept maps can be useful tools to illustrate change, or lack of change, in a student's conceptual understanding. While interviewing students to assess understanding of chemical concepts is not feasible for routine evaluation in chemistry classes, interviews are revealing of strengths and weaknesses in a student's understanding. Alternatively, concept maps can serve a similar purpose if students are taught to use this technique, and concept mapping also will facilitate meaningful learning (*32*).

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