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ABSTRACT

Within high school chemistry the topic of acids, bases, and pH is particularly challenging because robust understanding of the topic depends heavily on the student possessing deep concepts of atoms, molecules, ions, and chemical reactions. Since knowledge is acquired and stored in a dynamic structure, it was investigated in this study how knowledge changed as a result of the student's exposure to a particular type of learning task. Two areas of interest were targeted: the change in the students' understanding of acids, bases, and pH over the course of the treatment and the type of thought processes in which the students engaged while performing the treatment tasks. These understandings and thought processes were followed as a function of three levels of information presented by the technology: low level as represented by the use of chemical indicator solutions, intermediate level as represented by the use of a pH meter, and high level as represented by the use of a microcomputer-interfaced electronic pH probe. Reported in this paper are students' understandings prior to and after interacting with these technologies. Verbal data and drawings obtained in clinical interviews were used to construct concept maps and to analyze students' molecular concepts. Experts were also interviewed, and their concept maps were analyzed to identify critical nodes on their understanding of acids, bases, and pH. The concept maps and drawings were analyzed and two general conclusions reached: (1) students using microcomputer-based laboratory (MBL) activities appeared to construct more powerful and more meaningful chemical concepts; (2) the microcomputer group's high rates of both erroneous and acceptable links provide evidence that these students were positively engaged in restructuring their chemical knowledge. MBL appears to help students develop deeper understanding of acids, bases, and pH concepts, as indicated by the concept maps showing more detailed differentiation and integration. Examples of student's and expert's concept maps are appended. (KR)

The Effect of Level of Information as Presented by Different Technologies on Students' Understanding of Acid, Base, and pH Concepts

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Problem Statement

In this study we investigated students' understanding of acid, base, and pH concepts before and after a series of acid-base titrations using three technologies: chemical indicators, pH meters, and microcomputer-based laboratories (MBL). Each of these technologies provide the learner with a different level of information. Learners using the the chemical indicator could follow the color changes which occurred as the base was added to the acid. Learners using the pH meter could record the volume of base and the pH value after each addition of base, and they could also observe the movement of the pH meter needle after each addition of base. Learners using the microcomputer had available information on the pH value after each addition of base and could also observe the on-screen graph of pH vs. volume of base which was formed as the titration progressed. Our working hypothesis was that the level of information presented by the technology would interact with the instructional tasks to influence the understanding of acid/base chemistry developed by the learner.

Theoretical Background

Within high school chemistry the topic of acids, bases, and pH is particularly challenging because robust understanding of the topic depends heavily on the student possessing deep concepts of atoms, molecules, ions, and chemical reactions. Deep concepts are operationally defined in this study as concepts composed of propositional networks which are hierarchically organized, differentiated into branching subconcepts called nodes, and integrated by linking to other concepts (Novak and Gowin, 1984). A robust understanding is attained when a student has a propositional network which is sufficiently deep to allow the student to explain observed phenomena and to predict the behavior of new phenomena.

The student must also be able to represent this network of information, which we call knowledge, in one or more of the representational systems used in chemistry to organize and display chemical knowledge (Nakhleh, in review). In chemistry four interconnected representational systems are used: the macroscopic system in which matter has bulk properties, such as pH; the microscopic system in which matter is regarded as being composed of moving atoms, molecules, and ions; the symbolic system in which matter and chemical reactions are symbolized by equations, diagrams, and molecular structure drawings; and the algebraic system in which the relationships of matter are presented and manipulated using formulas and graphs (Gabel, Samuel & Hunn, 1987; Andersson, 1986; Ben-Zvi, Eylon & Silberstein, 1988; Yarroch, 1985; Herron, 1983). Krajcik (1990) refers to these interconnected representational systems as "integrated understandings." A student must constantly shift between these representational systems, employing each at appropriate times, when he or she engages in chemical reasoning about acids and bases.

In the study of acids and bases, the microscopic representation system is used in describing the fundamental model of the kinetic and particulate nature of matter, and the symbolic representation system is used in working with the equations which describe chemical behavior. For example, in the Brønsted-Lowry model acids are defined as substances which contribute an H^+ ion to an aqueous solution. Therefore students must have some understanding that an ion is a small, charged, mobile particle which can be produced by the dissociation of a substance in aqueous solutions. This dissociation process can be represented symbolically by an equation, such as

$$HCl_{(aq)} \rightarrow H^+_{(aq)} + Cl^-_{(aq)}.$$

The scientists' model of the particulate nature of matter is described in terms of atoms, molecules, and ions, and these topics are taught in the beginning of the course and used throughout the year. Chemical equations symbolize the dynamic and interactive nature of the particulate model and are also taught throughout the course. So in a real sense the students' understandings of acids, bases, and pH accurately reflect how well they have internalized and integrated a basic understanding of the particulate, kinetic nature of matter.

West, Fensham, and Garrard (1985) assert that students have access to varied sources of information: formal instruction in chemistry, public knowledge as available in various media, prior knowledge of science in general, and practical experiences in using commercial products. Knowledge is also acquired in informal situations, such as information acquired from parents and friends. Students of chemistry are constantly engaged in a process of turning this information into structured knowledge, and this process seems to be a difficult one for the majority of students.

As students struggle to organize this constant flow of information, Wittrock (1986, 1978, 1974) and Osborne and Wittrock (1983) argue that students generate knowledge structures which may be explored and described by various techniques. Posner and Gertzog (1982) use clinical interviews to probe students' knowledge of particular concepts, and Larkin and Rainard (1984) and Krajcik, Simmons, Lunetta (1988) argue that think-aloud protocols are a sensitive method of exploring students' problem solving techniques. Novak and Gowin (1984) advocate using concept maps to display, evaluate, and detect changes in students' knowledge structures. These knowledge structures are dynamic in that they constantly change by incorporating new information or deleting old information, and sometimes they change in unexpected and inappropriate ways. Osborne and Freyberg (1985) present evidence from a series of studies in New Zealand's Learning in Science Project to show that students' prior knowledge of a science topic and their everyday meanings for common science terms strongly influence, even hinder, the learning which occurs in the science classroom.

Some studies suggest that microcomputers used as data collection instruments have the potential to allow students to develop deeper and more detailed science concepts (Krajcik, 1990; Linn, 1987; Linn & Songer, 1988). The mechanism by which this apparent enhancement of learning functions is still being investigated, although both the computer's interactive nature and its immediate visual feedback have both been offered as initial hypotheses (Linn & Songer, 1988).

Since knowledge is acquired and stored in a dynamic structure, it was valuable in this study to investigate how knowledge changed as a result of the student's exposure to a particular type of learning task. Two areas of interest were targeted: the change in the students' understanding of acids, bases, and pH over the course of the treatment and the type of thought processes in which the students engaged while performing the treatment tasks. These understandings and thought processes were followed as a function of three levels of information presented by the technology: low level as represented by the use of chemical indicator solutions, intermediate level as represented by the use of a pH meter, and high level as represented by the use of a microcomputer-interfaced electronic pH probe. In this paper, we report on students' understandings prior to and after interacting with these technologies.

Design of the Study

Students were grouped by the level of technology employed. Each group performed the same sequence of titrations of three different acids by a base. Treatment group 1 used a chemical indicator to detect changes in pH. Treatment group 2 used a pH meter to detect changes in pH, and treatment group 3 used a microcomputer to detect changes in pH. Within each treatment the series of titrations consisted of a strong acid-strong base titration, a weak acid-strong base titration, and a polyprotic acid-strong base titration. Hydrochloric acid (HCl) was used for the strong acid, and acetic acid (CH_3CHOOH) was used for the weak acid-strong base titration. The polyprotic acid was phosphoric acid (H_3PO_4). In all of the titrations sodium hydroxide (NaOH) was the base, and all concentrations were 0.1 M. Changes in the understandings of the students were explored by using the verbal data and drawings obtained in pre and posttreatment semi-structured interviews to construct concept maps and to estimate the depth of their molecular concepts. We report changes in concepts of acids, bases, and pH as evidenced by the concept maps of the semi-structured interviews.

Fifteen senior high school students in grade 11 who completed a regular first-year chemistry course took part in the study. The students were selected by the method of purposeful sampling (Bogden & Biklen, 1982) in which participants in a study are chosen in order to facilitate the expansion of the developing theory. Bogden and Biklen argue that this sampling method is applicable in research designs which are inductive, that is, which look at many pieces of data and try to find common patterns or themes in the data. We suspected that students who have fragmented or incorrect concepts of acids, bases, and pH would develop more integrated concepts over the period of the treatment. This meant that very high achieving and very low achieving students were excluded from the study. High achieving students might already posses fully developed and well-integrated concepts, and lower achieving students might not have enough of a conceptual base to build upon. Therefore, we decided to select students who had an overall grade point average (GPA) of 2.80 to 3.20 or who had earned a cumulative chemistry grade of B- to B+. The students in the sample also reflected the ethnic diversity of the school: African-American, Asian-American, Caucasian, and Hispanic. We divided the students into three treatment groups by sex, class period, and GPA in an attempt to provide similar groups.

The data were collected in the last two months of the school year, so the students had essentially completed their unit on acid-base chemistry. The study was conducted in a suburban four-year high school on the east coast which served nine communities with a population of 150,000. The population ranged in socio-economic status from lower middle class to upper middle class. The school enrolled approximately 1800 students, and of these students slightly less than half completed a college admissions program of study.

Description of the Semi-structured Interviews

The pretreatment semi-structured interview consisted of an introduction and four sequences of examples and demonstrations. Specific questions in each section were asked of all the students, and following each question there were two to three levels of subquestions which could be used to probe further if students mentioned these topics or terms. For example, if a student stated that an acid could neutralize a base, the researcher would respond "You mentioned the term neutralization. What does that term mean to you?" The researcher was also free to probe student responses that did not fall into the preset categories, but in all cases the researcher asked every student the same fundamental set of questions. Interviews were audiotaped and and transcribed.

The posttreatment semi-structured interview was a parallel form in which the examples were changed and the fourth sequence was reversed so that the acid was added to the base.

First sequence. The student was shown a small bottle marked dilute acid, dilute base, pH 4, and pH 11 respectively. In each case the student was asked to tell what he or she knew about acids, bases, or pH respectively. Since the pilot study had revealed possible weak conceptions of molecules, atoms, and ions, each student was asked to draw on the interview data sheet what they might have seen if they could have looked through a very powerful magnifying glass at the solutions of acids, bases, pH 4, and pH 11.

Second sequence. The student was shown five labelled bottles or cans of ammonia, vinegar, dishwashing detergent, baking powder, and Coca-Cola.The student was then asked which of these products might contain an acid. Each selection was then discussed as to why it was an acid. Then the student was asked to select any bases which might be present, and the reasons for each selection were discussed. The next section of this sequence was a presentation of five small bottles labelled with the formulas HCl, NaOH, CH_3COOH, NH_3, and NaCl, which represent hydrochloric acid, sodium hydroxide, acetic acid, ammonia, and sodium chloride respectively. The student was asked to select which ones were acids, then the reasons for the selection were discussed. Finally, the student was asked to select which of the bottles labeled with formulas were bases, discussing the reason for each selection.

Third sequence. Students observed the changes that occurred when the acid and the base were mixed together. The student was shown the bottle marked dilute acid and the bottle marked dilute base. About 50 mL of the acid was poured into a beaker, and the student was told that some phenolphthalein would be added. The student was then asked to state what they knew about phenolphthalein. If they were uncertain, the first response was to state that phenolphthalein was an acid/base indicator. The student was then asked to tell what they knew about acid/base indicators. If the student was still unsure, the final statement was that the phenolphthalein would change color if any change occurred in the solution. Two drops of phenolphthalein were added to the acid in the beaker. Then the base was slowly added to the acid, stopping to swirl the liquid in the beaker so that the student could see the pink color form and then fade before changing permanently to pink. The student was then asked to describe what had happened to the acid, to the base, and to the pH. Finally, the student was asked to state what they thought was in the beaker after all of the base had been added. At the end of this section students were also asked what they would see if they looked in the beaker with their powerful magnifying glass.

Fourth sequence. Students were presented with two possible graphs, on separate sheets of paper, of pH versus volume of base added and were asked to select which graph best described what had happened to the pH when the base was added to the beaker. The graphs were presented at the same time and in the same order to each student. Also each student was told again that the acid was in the beaker and the base was added to the acid. The graph the student selected as correct was marked #1, and the other graph was marked #2 and laid to one side. The student was then asked why he/she had picked the #1 graph. Next the student was first asked to circle and label the part of the graph that showed the system was acidic, then the part that was basic, and last the part that was neutral. Finally, the student's attention was drawn to the steep vertical rise in the grap:: where the acid and base rapidly and completely change to water and a salt, which is neutralization. The student was asked to explain what they thought was happening in this vertical region. In the last section of this sequence the student was shown the graph marked #2 which the student said did not describe what he/she saw happening in the beaker as the base was added to the acid. The student was asked what this graph did describe.

Expert Interviews

In order to have a standard against which to compare the students' interviews and to provide some estimate of validity for the interviews, four experts in the field were give the same pretreatment or posttreatment interviews as the students. Of the four who were interviewed, two held the Doctor of Philosophy in Science Education with expertise in chemical education, one was finishing a Master's in Science Education, and one held a Doctor of Philosophy in Chemistry. Two experts received the pretreatment interview, and two received the posttreatment interview. All of the experts stated that the interview effectively covered the important topics in undergraduate level acid/base chemistry.

Analysis of the Interviews

The interviews were analyzed by concept mapping. Concept mapping was selected as the most sensitive tool to detect shifts in understanding from pretreatment to posttreatment. A sense of the magnitude and direction of the change could also be obtained by scoring the maps and comparing the gain scores pre to post for each student and by comparing the average gain scores across treatment groups. The students' drawings associated with the interviews were used to clarify and confirm the propositions extracted from the interviews.

Analysis of Concept Maps. In order to construct meaningful concept maps of such a complex structure as knowledge of acids, bases, and pH, decision rules had to be constructed and strictly followed. Initial attempts at mapping quickly made it clear that one single concept map encompassing the three basic concepts of acids, bases, and pH would be difficult to interpret. Therefore it was decided to break the interview concept maps into three separate maps, one for acids, one for bases, and one for pH. This meant that six concept maps, three pretreatment maps and three posttreatment maps, were prepared for each student.

These three major divisions of the concept map followed the structure of the interview very naturally, which made it fairly easy to construct the maps. Each interview had sections describing acids and selecting examples of acids, describing bases and selecting examples of bases, and describing pH and the interrelationships between acids and bases as expressed in the neutralization reaction. The appropriate sections were used to construct each map.

Selecting Propositions. Each interview was read and statements and phrases which revealed the student's propositional knowledge about either acids, bases, or pH were selected. For example, statements which contain phrases such as "acids are. . ." or " I believe that . . ." would be selected. These propositions were used to draw the actual concept maps. The student's exact wording was used whenever possible in order to closely conform to the statements made in the interview. A record was kept of each decision rule that was made to maintain consistency in map construction.

However, three general exceptions were made to this rule of using the student's own words. First, examples that the student gave, such as "lemon juice is an acid', were drawn by connecting the concept labels 'Acids' and 'lemon juice' and using the word 'as' on the connecting line to denote that the relationship being shown was that of an example of an acid. On a concept map, the statement would read " Acids as lemon juice." All examples were treated in this manner. Second, the concept map of the pH graph was always connected to the overall pH concept map by the proposition "pH can be shown as pH graphs." Third, the propositions "pH graphs place Acids ...," "pH graphs place Bases....," and "pH graphs place neutral...." were generally used to indicate the location of these areas on the students' graphs. This provided a standardized method of handling the examples provided in the interview and also provided a standard way of linking the pH graph discussion into the pH concept map.

See Figure 1 and Figure 2 for examples of concept maps. Acids, pH, and bases are always enclosed in an irregular shape in order to clearly mark them as one of the three major concepts. Any link between acid and base, acid and pH, or base and pH is a cross link between two different areas of knowledge. Nodes which are repeated across maps for one interview are in a rectangular shape.

[Insert Figures 1 and 2 about here.]

Mapping Examples. Another decision rule had to be implemented in regard to examples, since the interviews contained two types of examples: examples spontaneously generated by the student and examples which were presented to the student during the interview. Examples presented in the interviews were to be drawn from the label "Acids" to the example and then the example could refer back to the specific chemical or physical property which had prompted the selection. As an example, a student's proposition that "ammonia is an acid because it is strong" would be graphed as "Acids as ammonia because it is strong", which would be a reference to the concept label "strong" which would already be present on the map in some proposition such as "Acids are strong." (See Figure 1 for an illustration.) This was done in order to help identify what were the nodes or concept labels in the student's understanding to which he or she constantly referred when making decisions about what constituted an acid or a base. At a later step in the analysis, these nodes were denoted as critical nodes and were used to look for shifts in understanding and for common patterns within groups.

Examples which were generated spontaneously were mapped from the specific chemical or physical property which had generated the example. For example, a student's proposition that "Acids taste sour, like pickles" would be mapped as " Acids taste sour as pickles." The word "pickles" would not be generally referenced by any other proposition. Figure 1 provides a concept map which contains both types of examples.

Scoring the Concept Maps

Propositions and Examples. The completed concept maps were scored according to a common algorithm presented in Novak and Gowin (1984). All acceptable propositional relationships which did not involve cross linking were assigned a point value of one. Also all acceptable examples were assigned a value of one. If an example was judged unacceptable, but its subsequent propositions were acceptable, then those subsequent propositions were not counted toward the total map score.

Cross Links. A cross link was considered an important indicator of integrated, meaningful learning, and specific rules were developed as to what should count as a cross link and what should not. A cross link could have occurred in one of two ways. First, a student could have related two different nodes, coming from two different lines on the concept map. For example, a student could have stated that acids are strong and then also have stated that acids neutralize bases to become less strong. Figure 1 gives an example of such a cross link. However, the link between an example and an acceptable reason for selecting that example did not count as a cross link.

In a second type of cross link, a student could have invoked a connection between two of the three major concepts of the map, such as making a statement that acids neutralize bases, which indicated that the student was connecting two substantially different areas of the concept map. Figure 1 also gives an example of this type of cross link.

Because a cross link indicated knowledge integration, an acceptable cross link was scored at 10 points. Novak and Gowin (1984, page 107) state that "cross links that show valid relationships between two distinct segments of the concept hierarchy signal possibly important integrative reconciliations. . . ." He also recommends that linkages, such as cross links, which signal integrative reconciliation be assigned a score value between 10 and 20 times the score value of a valid relationship. Therefore a score value of 10 points for a cross link does not seem unreasonable.

Meaningful, integrated learning, as evidenced by crosslinking, resulted in a substantial difference between the pretreatment and posttreatment concept map scores. Because the cross links were important to the analysis, a detailed set of rules was developed as to what counted as an acceptable cross link and what did not count. For example, a cross link had to occur in different lines of descent from the main concept and could not occur between an example and a reason the example was selected. Figure 1 shows an example of cross linking.

Hierarchy. Many concept map scoring schemes include a score for acceptable levels of hierarchy present in the map. Typically this score is five points for each acceptable level (Novak and Gowin, 1984; Wallace and Mintzes, 1990). However, in studies where hierarchy is scored, students have drawn their own concept maps after having been trained to do so by the researcher. In that situation, the hierarchies on the maps are a valid reflection of the student's actual understanding. In this study, the concept maps were drawn by the researcher using the interview data, and it was decided that hierarchies could not be validly inferred from the interview data.

Scoring the maps. The total score for each concept map was obtained by adding all the scores on each section of the map. Each section of the map was cross-checked by the researcher to make sure that some cross links were not counted twice. For example, in discussing acids a student could say that acids neutralize bases, and then in discussing bases the student could turn the statement around and state that bases neutralize acids. Both of these statements are accessing the same parts of the student's understanding and should only be counted once. Figure 18 is an example of a high scoring map, and Figure 8 is an example of a low scoring map. Figure 7 is an example of a medium scoring map.

In addition, a total score of unacceptable relations in each concept map was obtained using the same scoring procedure. This was done in order to estimate unacceptable changes that could have occurred in students' understandings over the course of the treatments.

Reliability of Concept Maps. A Ph. D. in science education with specialized preparation in chemistry was trained by the researcher to construct and score concept maps in order to calculate an interrater reliability. The rater was trained using two concept maps chosen randomly, and the rater was provided with a written list of the decision rules which guided the creation of the original maps. Then the rater constructed three randomly selected concept maps, and a reliability of 0.82 was calculated by dividing the number of agreed upon nodes by the total number of nodes on the original map. The rater then scored three randomly selected maps, and an interrater reliability of 0.83 was calculated by dividing the total number of agreed upon relationships by the total number of relationships on the original map.

Construction and Use of Experts' Concept Maps

The interview transcripts of the chemical experts were reviewed, and concept maps of their understandings were drawn and scored. The expert map scores were used in two ways. First, the experts' scores were very similar, with an average of 157 points. This indicated that the interview scripts were reliable and gave consistent scores. Second, the maps were examined to identify the critical nodes which were referenced most frequently by the experts in explaining their knowledge during the interview. These critical nodes were then used to assess the students' critical nodes to see if their thinking had shifted toward the understanding of an expert. Wallace and Mintzes (1990) used the notion of critical concepts in a similar manner.

Critical nodes are defined as nodes around which knowledge appears to be organized. We operationalized defined critical nodes as nodes which were referenced by relationship lines coming into the nodes at least three times. This meant that the student or expert had to reference that node with at least two cross links in the interview. Relationship lines going out of the node to other nodes were not counted in this process because outgoing lines do not indicate integrative thinking. A further restriction on a critical node was that 50% of the lines coming into the node had to express an acceptable relationship to other parts of the map.

Results and Analysis

Equivalence of the Treatment Groups. We examined the treatment groups for any differences in group composition which might bias the findings. We found three indicators which support the claim that the groups were reasonably equivalent before treatment. First, the groups were equivalent on GPA and gender. Second, at the end of the year students were administered a county chemistry examination which covered the major topics of the year's course in chemistry. The average scores of the groups on this examination were equivalent. Third, the concept map scores for pretreatment interviews of the three groups were again reasonably equivalent, although the pH meter group scored somewhat lower than the other two groups.

Concept Map Scores of Acceptable Relations and Cross Links. Table 1 presents the concept map scores in two ways: unweighted relationships, in which all valid relationships are scored as one point, and weighted relationships, in which all valid relationships are scored as one point and all valid cross links are scored as 10 points. All groups show some positive gain in their concept map scores. Table 1 indicates that the microcomputer group shows more change than the other groups. The pH meter group showed the smallest difference, a 16% increase in the weighted concept map scores from pretreatment to posttreatment, while the microcomputer group experienced the greatest change, a 63% increase in the weighted score. The chemical indicator group registered a 38% change in the weighted scores. Looking at the students across groups, twelve of the students evidence positive change in the map scores; two students had scores which changed in a negative direction.

[Insert Table 1 about here.]

Concept Map Examples

pH meter group. Figures 2 and 3 illustrate a change representative of the pH meter group in the acid concept from pretreatment to posttreatment for student #0206.DG. Figure 2 also illustrates a map that received a relatively low score because most of the relationship are linear and only a few cross links exist.

[Insert Figure 3 about here.]

The pH meter group had the least change in concept map scores. The number of acceptable relationships and examples for this student increased from 21 to 23, and the number of acceptable cross links increased from two to three. In the pretreatment map the map shows acceptable cross links from acids to pH and from pH to strength. The posttreatment map contains a new, correct concept that acids react with bases, but the map also indicates that the product is a mixture rather than two new compounds.

These maps also show the persistence of some unacceptable concepts. The pretreatment map shows a proposition that acids are made of molecules and contains five branches which differentiate this proposition further. This was not accepted as a valid proposition because acid solutions characteristically contain a mixture of ions and molecules. Strong acids are completely ionized and have no molecules in solution, and weak acids have only a few ions and many molecules in the solution. The posttreatment map still contains the proposition that acids are made of molecules and a two-level hierarchy has developed to explain this proposition further.

Chemical indicator group. Figures 4 and 5 contain the pretreatment and posttreatment acid concept maps for #0103.CP which are representative of this group. The number of acceptable relationships and examples increases from 17 to 23 and the number of cross links decreases slightly from five to four. Both maps have acceptable cross links between acids, bases, and pH; however, the acceptable proposition that acids contain hydrogen does not appear until the posttreatment map.

[Insert Figures 4 and 5 about here.]

The pretreatment map shows that substances were identified as acids on the basis of their harmfulness because the Coca Cola, vinegar, and ammonia are linked to the term harmful. The posttreatment map shows a shift toward identifying substances on the basis of the hydrogen they contain, as for example HNO_3 and H_2SO_4. Note, however, that NH_3 and $Ba(OH)_2$ are also identified as acids using this rule; therefore, the student's differentiation of this rule is incomplete.

Microcomputer group. Figures 6 and 7 contain the pretreatment and posttreatment acid concept maps for #0302.WC which are representative of this group. The number of acceptable relationships and examples increases from 22 to 24, and the number of cross links increases from one to six. The pretreatment map shows several acceptable examples, and there is one acceptable cross link that acids interact with bases. The posttreatment map has about the same number of acceptable examples and relationships, but the number of acceptable cross links has risen. Cross links occur between acids and bases, between hydrogen ion and hydrogen, between elements and bases, between pieces and elements, between bases and phenolphthalein, and between oxygen and hydrogen. These cross links could signal important integrations of concepts.

[Insert Figures 6 and 7 about here.]

These maps also illustrate a persistent alternative conception this student holds about bubbles. The pretreatment map shows that bubbles are associated with baking powder and Coca Cola, both of which the student gives as examples of acids. The posttreatment map contains a proposition that acids contain bubbles and that these bubbles are made of molecules and ions.

The maps also show a positive conceptual change in that the role of hydrogen is more emphasized in the posttreatment map than in the pretreatment map. The posttreatment map also shows a shift from a molecular representation of acids toward a more acceptable proposition that the molecules are broken into smaller pieces which have a plus charge, as the hydrogen ion. There is also a cross link made between the hydrogen ion and the element hydrogen. Therefore this map shows a shift toward a more acceptable understanding of acids as containing hydrogen ions.

Concept Map Scores of Unacceptable Relations and Cross Links. In order to gain a more accurate estimate of the treatment effects, error rates must also be taken into consideration because no instructional sequences were used in this study. Therefore students might generate many acceptable relationships and also might generate many unacceptable relationships. The concept maps were rescored using the unacceptable relationships and disregarding the acceptable ones. These data are shown in Table 2. In this table a negative number signifies a reduction in the errors on the concept map.

[Insert Table 2 about here.]

These data show a different trend from the data in Table 1. Here the chemical indicator group shows an average reduction in the weighted error score of 14%, while the microcomputer group had an average increase in the weighted error score of 49%. The pH meter group experienced a more moderate average increase in the weighted error score of 5%.

Chemical indicator group. This group showed the greatest weighted error reduction of 14%. Within the group, Table 2 shows that one student, #0111.DH, had a slightly increased error score due to cross linking, but the other group members showed a decline in unacceptable linkages.

Figures 8 and 9 display the pretreatment and posttreatment maps of the base concept of student #0114.TH which are representative of this group. The maps show approximately the same number of relationships, but the proportion of unacceptable linkages declines from 15 to nine. The posttreatment map also contains clear propositions that bases can react with acids and that bases have a pH, which are important and appropriate cross links. However, the student has also increased inappropriate cross links to strength, which indicates an increased belief that acids generally have less strength than bases. These maps illustrate the point that a simple reduction in the number of incorrect relations may also be accompanied by an increase in inappropriate cross links. In summary, the maps show that this student decreased the number of his or her overall misunderstandings but that he or she strengthened an alternative conception about strength.

[Insert Figures 8 and 9 about here.]

pH meter group. Table 2 indicates that students within the pH meter group exhibit some variation in error patterns. On the weighted scores, the group increased its error score by about 5%, with two students showing an increase and two students showing a decline. On the unweighted scores, the error score declined by 8%, again with the two students showing an increase and two students showing a decline.

Figures 10 and 11 display the pretreatment and posttreatment maps of student #0209.DR, representative of this group, who declined in unweighted relationships but increased in the weighted cross links. The pretreatment map is very linear and undifferentiated; it has one appropriate and two inappropriate cross links to acids. The posttreatment map contains approximately the same number of inappropriate relations, but the number of inappropriate cross links has doubled to four. The posttreatment shows more integration and differentiation, as evidenced by cross linking and branching, around the concepts of strength, harmfulness, and number of elements in the compound. In sum, this student seems to have solidified his or her understanding of bases around a number of alternative conceptions.

[Insert Figures 10 and 11 about here.]

Microcomputer group. This group had the greatest increase in error score of all the groups. Their average unweighted increase was 24%, and their average weighted increase was 49%. This indicates that they formed a number of inappropriate relations and cross links. However, this group also increased their acceptable weighted score by 63%. This indicates that they formed many appropriate relations and cross links as well as inappropriate ones. The microcomputer group shows evidence of high engagement in the MBL activity and basically needs instruction to channel this engaged thinking in an acceptable direction.

Figures 12 and 13 illustrate this point. These pretreatment and posttreatment base concept maps of student #0312.NM, representative of this group, show that the total number of relationships doubled from pretreatment to posttreatment. Also the posttreatment map contains more branches and cross links. The pretreatment map contains one appropriate cross link to acids and two inappropriate cross links to hydrogen. However, the posttreatment map contains six appropriate cross links between bases and pH, between pH and acids, between equations and OH, between ratio and other elements, between

$Ba(OH)_2$ and pH 10, and between plus and attraction. The posttreatment map also contains more inappropriate relations and cross links.

[Insert Figures 12 and 13 about here.]

The maps also show that the student's molecular propositions changed in an appropriate direction. The pretreatment map only references the general term "elements", but the posttreatment map shows a more clearly defined subset of propositions attached to the term OH which recognize that the OH and H have negative and positive charges.

Critical Nodes on the Concept Maps

The concept maps of the experts were used to determine the critical nodes around which experts appear to organize their knowledge. Figure 14 shows that this expert organized his or her knowledge of acids around the nodes for hydronium ions, strong acids, anions, and molecules. All of the critical nodes for the experts were identified and six nodes were important in every experts' map: H^+ ions, water, OH^- ions, neutral, solutions, and concentration. These six were then considered to be central to a successful understanding of acid/base chemistry. For the sake of brevity, the six critical nodes of H^+ ions, water, OH^- ions, neutral, solutions, and concentration which were identified in the experts' concept maps will be referred to as expert critical nodes.

[Insert Figure 14 about here.]

Students' maps were then examined to identify the acceptable critical nodes around which their knowledge appeared to be organized and to ascertain if any of them were using expert critical nodes. Tables 3, 4, and 5 indicate the number of acceptable critical nodes which where identified in the students' pretreatment and posttreatment concept maps. A pattern emerges which is similar to the pattern of the concept map scores. The microcomputer group experienced the greatest increase. The students' critical nodes were also compared to the experts' critical nodes. If students used the same critical nodes as did the experts, that node is starred in Tables 3, 4, and 5.

[Insert Tables 3, 4, and 5 about here.]

In the chemical indicator group the number of expert critical nodes is reduced by one from pretreatment to posttreatment. Figures 15 and 16 illustrate this point. In Figure 15, which is the pretreatment acid concept map, the student used hydrogen ions as a critical node. This is also an expert critical node. In the posttreatment map shown in Figure 16, however, this expert critical node has vanished, and the posttreatment map shows that knowledge is organized around harmfulness and hydrogen, both of which have inappropriate relations coming into the node.

[Insert Figures 15 and 16 about here.]

In the pH meter group the number of expert critical nodes increases by one, and in the microcomputer group the critical nodes increase by 2. However, the importance of these critical nodes can be more accurately gauged if the number of times that they are referenced is also calculated. When this is done, a pattern similar to the one noted before in the concept map scores emerges. The chemical indicator group's references to its expert critical nodes increase by two, from 16 to 18 times. The pH meter group's references increase by four, from three to seven times. However, the microcomputer group increases its references to expert critical nodes by 18, from 18 to 36 times.

The contrast between the pH meter group and the microcomputer group can be illustrated by Figures 17 and 18. Figure 17 shows the posttreatment pH map of a student in the pH meter group. This map has only one critical node for neutral, which is also an expert critical node, and the critical node is accessed by a minimum of lines. On the other hand, Figure 18 shows the posttreatment pH map of a student in the microcomputer group. This map contains critical nodes for hydrogen, neutral, OH- ions, pH 7, and water which have many appropriate incoming lines and which are well-integrated into the student's knowledge structure. Also the nodes for neutral, OH-, and water are expert critical nodes as well.

[Insert Figures 17 and 18 about here.]

The same pattern holds when number of times that these nodes were referenced is calculated. The chemical indicator group's references increase by 36, from 36 to 72, and the pH meter group increases its references by 6, from 21 to 27. The microcomputer group increases its references by 59, from 51 to 110. Again, the MBL activity appears to encourage students to engage in restructuring their chemical knowledge.

Figures 16, 17, and 18 again illustrate this point. Figure 16 is an acid concept map for a chemical indicator student, and it has no acceptable critical nodes. In addition, it displays a strong alternative conception built around harmfulness. Figure 17 is a pH concept map for a pH meter student containing only one acceptable critical node. Figure 18, however, is a pH concept map of a microcomputer student, and it is constructed around several appropriate critical nodes. Some inappropriate links are made, especially to the nodes for power and strength, but generally this map shows a better integration of knowledge than the other two maps.

Conclusions

From our analysis of the concept maps and drawings, we made two general conclusions. First, students using microcomputer-based laboratory activities appeared to construct more powerful and more meaningful chemical concepts. The posttreatment concept maps showed greater differentiation and integration of concepts. By the end of the treatment, the students in this group expressed more acceptable subconcept nodes, linked these nodes together with more acceptable propositions, and built more cross links between their nodes. They also built their maps around more acceptable critical nodes, including several expert critical nodes. Although these students did exhibit weakness in their understandings of ionization and neutralization reactions, their posttreatment knowledge of acids, bases, and pH was was more detailed and more integrated than the knowledge of the other groups. We interpret this to mean that the microcomputer-based laboratories had a substantial influence on their understandings of acid, base, and pH concepts.

Second, the microcomputer group's high rates of both erroneous and acceptable links provide evidence that these students were positively engaged in restructuring their chemical knowledge. Students apparently construct more concepts using microcomputer-based laboratories, but careful analysis of the laboratory task, directed teaching, and class discussion are needed to counteract the formation of inappropriate concepts. For example, extensive pre-laboratory discussions could be used to clearly focus the student's attention on what are the important clues to observe as the laboratory progresses, to clearly state the objectives of the experiment and to encourage the students to recall what they know about acids and bases and how that knowledge applies to the laboratory activity. Post-lab discussions are necessary to uncover and confront alternative conceptions which may arise during the course of the activity and to remind the students of the purpose of the laboratory and to encourage the students to relate what they found in the laboratory activity to the cognitive knowledge taught in lecture. These instructional tactics allow the student to link together the various components of his or her understandings into a more coherent whole.

Educational Significance of the Study

MBL appears to help students develop deeper understanding of acids, bases, and pH concepts, as indicated by the concept maps showing more detailed differentiation and integration. MBL also appears to be effective in remediating students' weak models of matter because the microcomputer group made the greatest positive shift in their models, but how this happens is not clear. It may be that the graph which is constantly displayed on the screen allows the students to free their short-term memories from the burden of processing the information generated by the titration and allows them sufficient time to reflect on what might be happening on the molecular level, to access their long-term memories, and to essentially restructure their information into new knowledge. It may also be that the visual image of the graph screen is sufficiently vivid to be retained as a strong and easily retrievable memory.

Implications for Future Research. This study indicates that microcomputer-based laboratories can help students form robust understandings of acid and base concepts. However, microcomputer-based laboratories seem to be a two-edged sword in that they focus attention so powerfully that students might easily and enthusiastically create inappropriate understandings. Therefore research needs to be done on effective methods of using microcomputer-based laboratories in teaching. For example, the value of pre-laboratory and post-laboratory discussions as a means of identifying and confronting alternative conceptions needs to be examined. What is the appropriate role of a pre-laboratory discussion? What is the appropriate role of a post-laboratory discussion? Are there commonalities in these roles?

More research also needs to be done on what attributes of MBL cause it to work so well, and the suggestion that MBL might function as a auxiliary memory device for the student certainly needs further exploration. For example, what role does graphing the data on the screen play in helping students develop more appropriate understandings? How are visual images, such as graphs, stored in long-term memory? How are visual images used in the integration of knowledge?

This study also indicates that concept mapping may be a powerful and sensitive technique for studying conceptual change. This use of concept mapping is relatively recent and ought to be explored further.

This study also began to clarify what are students actually thinking about when they engage in a laboratory activity. A laboratory experiment is a complex learning environment, and students may become so overwhelmed with the task at hand that they literally have no memory space left with which to think conceptually. Much more work needs to be done on students' thoughts during a laboratory activity.

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Table 1

Concept Map Scores of Weighted and Unweighted Acceptable Relationships by Treatment Group

Group	Pretreatment		Posttreatment	
	Unweighted Relations	Weighted Cross Links	Unweighted Relations	Weighted Cross Links
Chemical Indicator Group				
0103.CP	55	167	76	211
0111.DH	47	146	68	248
0111.AC	29	29	36	54
0113.SS	50	158	63	189
0114.TH	45	99	59	126
Average	45	120	60	166

Unweighted difference = +15 points or +33%.

Weighted difference = +46 points or +38%.

Group	Pretreatment		Posttreatment	
pH Meter Group				
0204.SK	45	90	33	60
0206.DG	41	104	59	122
0207.CS	47	137	32	95
0209.DR	18	45	49	157
Average	38	94	43	109

Unweighted difference = +5 points or +13%.

Weighted difference = +15 points or +16%.

Group	Pretreatment		Posttreatment	
Microcomputer Group				
0301.JC	55	127	84	192
0302.WC	53	107	65	196
0305.LL	29	83	39	111
0312.NM	62	161	101	299
0315.JM	34	70	63	99
Average	47	110	70	179

Unweighted difference = +23 points or + 49%.

Weighted difference = +69 points or +63%.

Table 2

Concept Map Scores of Weighted and Unweighted Unacceptable Relationships by Treatment Group

Group	Pretreatment Unweighted Relations	Pretreatment Weighted Cross Links	Posttreatment Unweighted Relations	Posttreatment Weighted Cross Links
Chemical Indicator Group				
0103.CP	46	172	47	164
0111.DH	39	93	39	129
0111.AC	82	271	77	248
0113.SS	68	212	68	149
0114.TH	67	175	47	110
Average	60	185	56	160
Unweighted difference = -4 points or -7%.				
Weighted difference = -25 points or -14%.				
pH Meter Group				
0204.SK	50	140	36	45
0206.DG	46	91	45	81
0207.CS	58	184	62	287
0209.DR	100	244	93	282
Average	64	165	59	174
Unweighted difference = -5 points or -8%.				
Weighted difference = +9 points or +5%.				
Microcomputer Group				
0301.JC	30	93	21	48
0302.WC	63	216	73	293
0305.LL	36	63	27	99
0312.NM	71	242	104	482
0315.JM	50	188	86	266
Average	50	160	62	238
Unweighted difference = +12 points or +24%.				
Weighted difference = +78 points or +49%.				

Table 3

Acceptable Critical Nodes in Concept Maps for the Chemical Indicator Group

Group	Pretreatment Nodes	Times Referenced	Posttreatment Nodes	Times Referenced
0103.CP	Harmfulness	3	Hydrogen	5
	Solution*	4	Midpoint	3
	Water*	3	Neutral*	4
			pH 7	6
			Solution*	5
0111.DH	Hydrogen	3	Oxygen	3
	OH^- ion*	3	Strength	14
	Oxygen	3	Together	3
			Water*	4
0111.AC	Clearness	3	Particles	3
	H^+ ion*	3		
0113.SS	Neutral*	3	Neutral*	5
	Vinegars	3	pH 7	3
			Strength	7
0114.TH	pH 7	5	Elements	4
			Midpoint	3

Note. Nodes which are also expert critical nodes are starred.

Table 4

Acceptable Critical Nodes in Concept Maps for the pH Meter Group

Group	Pretreatment Nodes	Times Referenced	Posttreatment Nodes	Times Referenced
0204.SK	Midpoint	4	None	None
	Strength	4		
0206.DG	Neutral*	3	Neutral*	4
	pH 7	3		
	Strength	7		
0207.CS	None	None	Neutral*	3
0209.DR	None	None	Burning	3
			Harmfulness	6
			Strength	11

Note. Nodes which are also expert critical nodes are starred.

Table 5

Acceptable Critical Nodes in Concept Maps for the Microcomputer Group

Group	Pretreatment Nodes	Times Referenced	Posttreatment Nodes	Times Referenced
0301.JC	H^+ ions*	3	H^+ ions*	3
	Hydrogen	3	Hydrogen	3
	OH^- ions*	5	Middle	3
	pH 7	3	Neutral*	4
	Water*	3	OH^- ions*	3
			Solution*	3
			Water*	3
0302.WC	Hydrogen	3	Hydrogen	8
	OH^- ions*	3	Phenolphthalein	4
			Sour	3
0305.LL	Scale	3	pH 7	5
			Strength	4
0312.NM	Color	3	Elements	3
	pH 7	3	Equations	3
	Scale	3	Hydrogen	13
	Structure	4	Negative charge	5
			Neutral*	6
			OH^- ions*	8
			pH 7	3
			Ratio	10
			Water*	9
0315.IM	Chemicals	5	Components	3
	Element	3	Elements	4
	Water*	4	Oxygen	7
			Sour	3

Note. Nodes which are also expert critical nodes are starred.

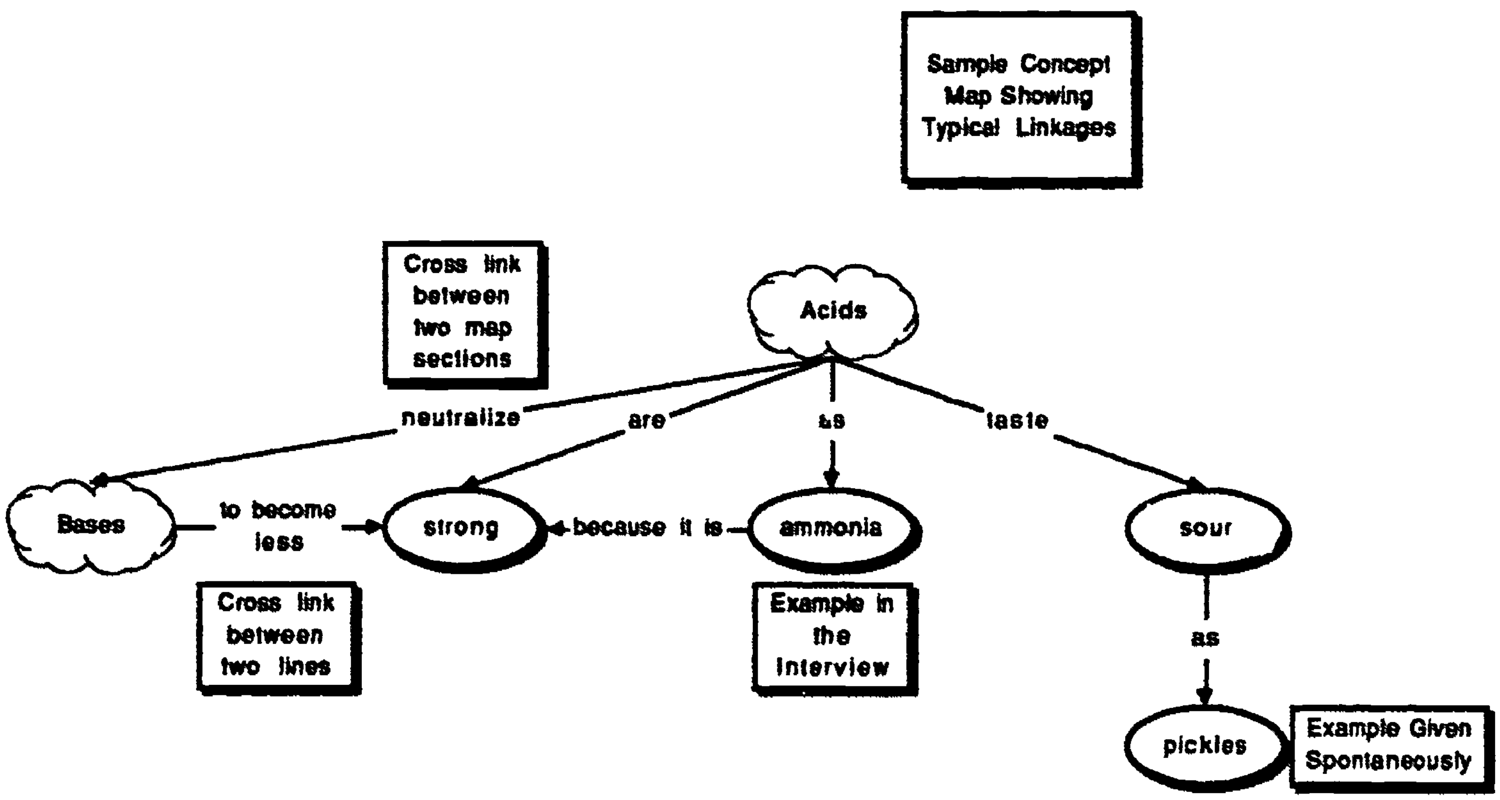

Figure 1. A sample concept map demonstrating the mapping of examples and containing examples of cross linking.

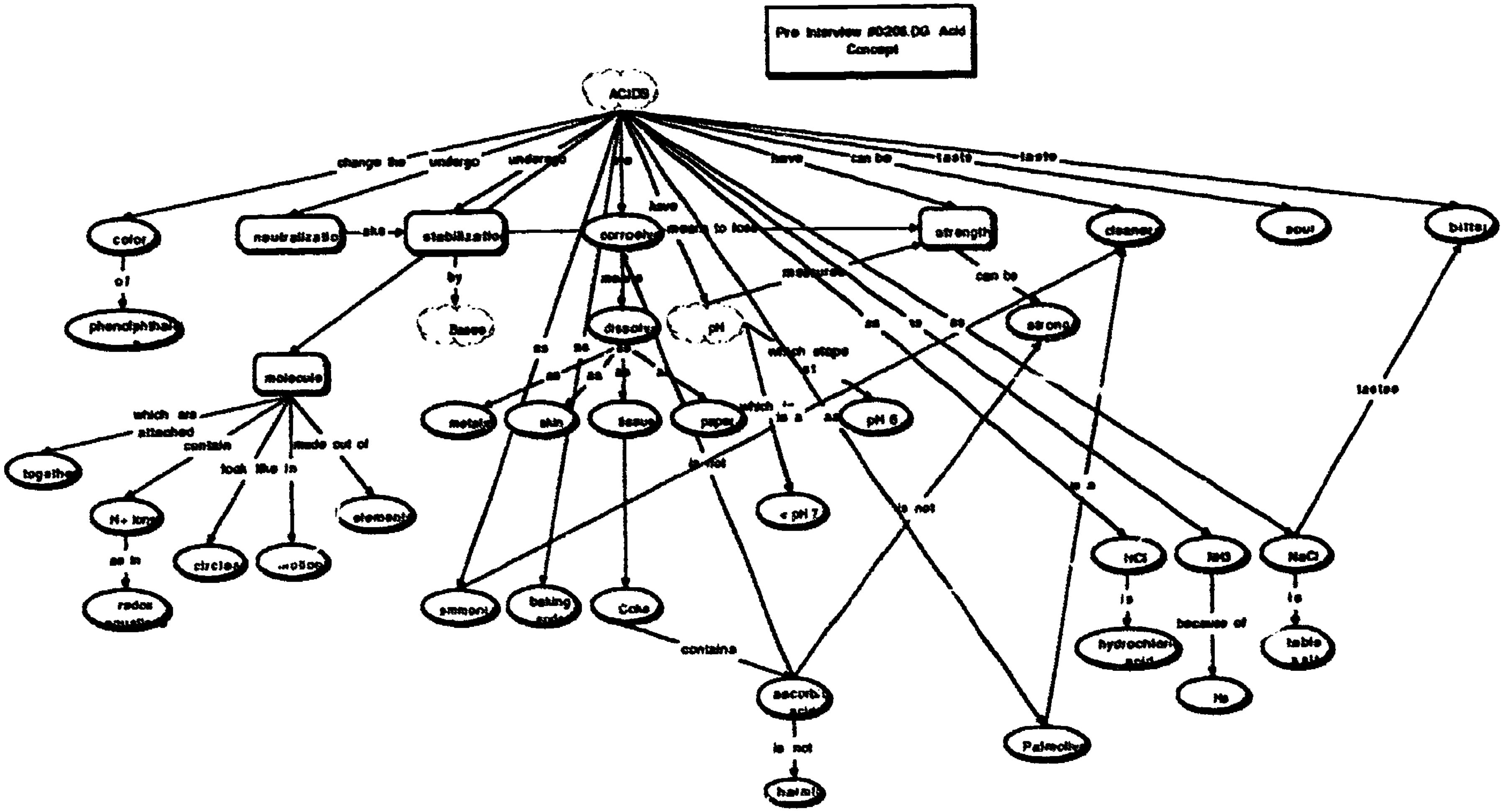

Figure 2 Pretreatment acid concept for #0208.DG, pH meter group.

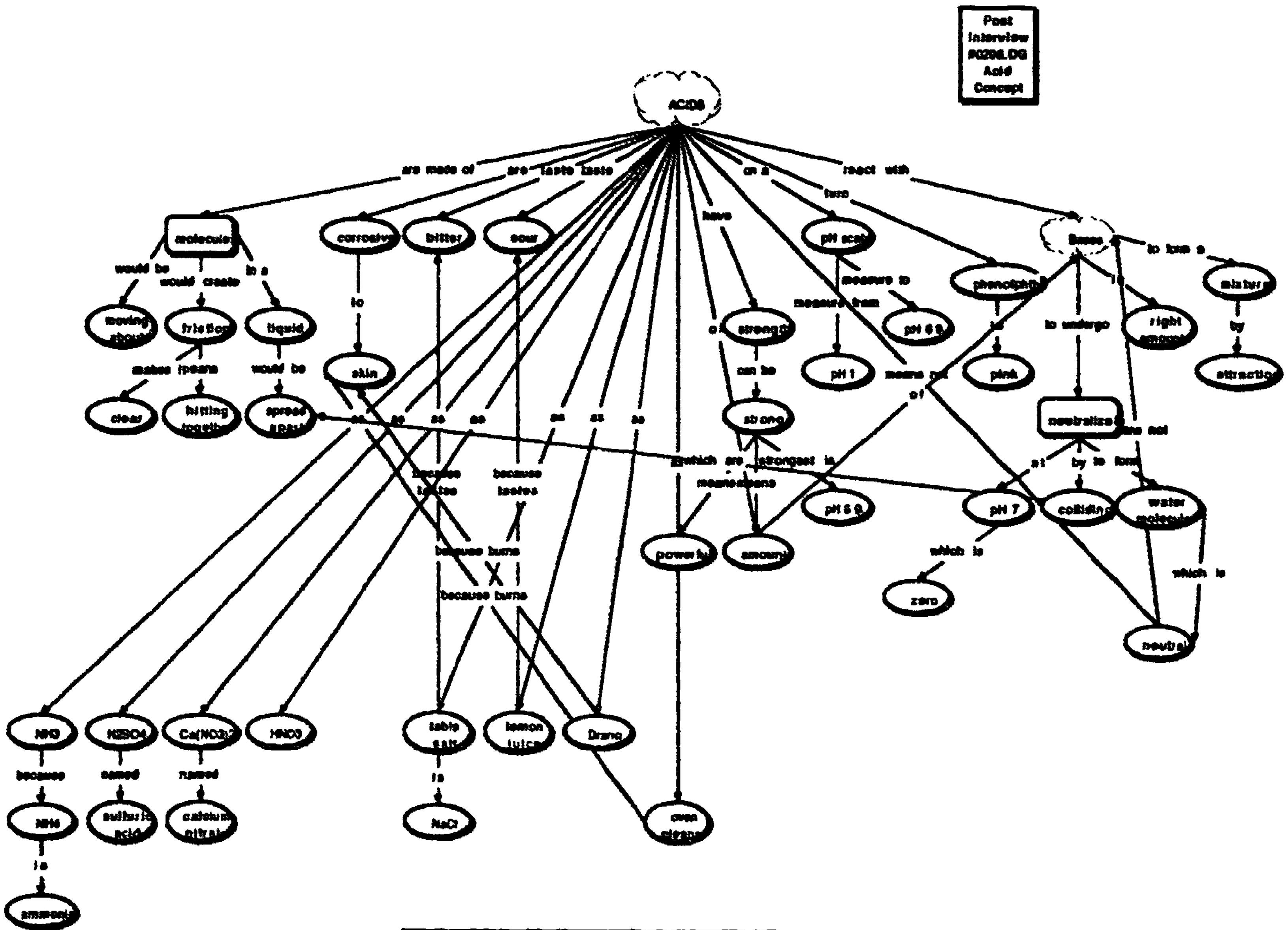

Figure 3. Posttreatment acid concept for #0208.DH, pH meter group

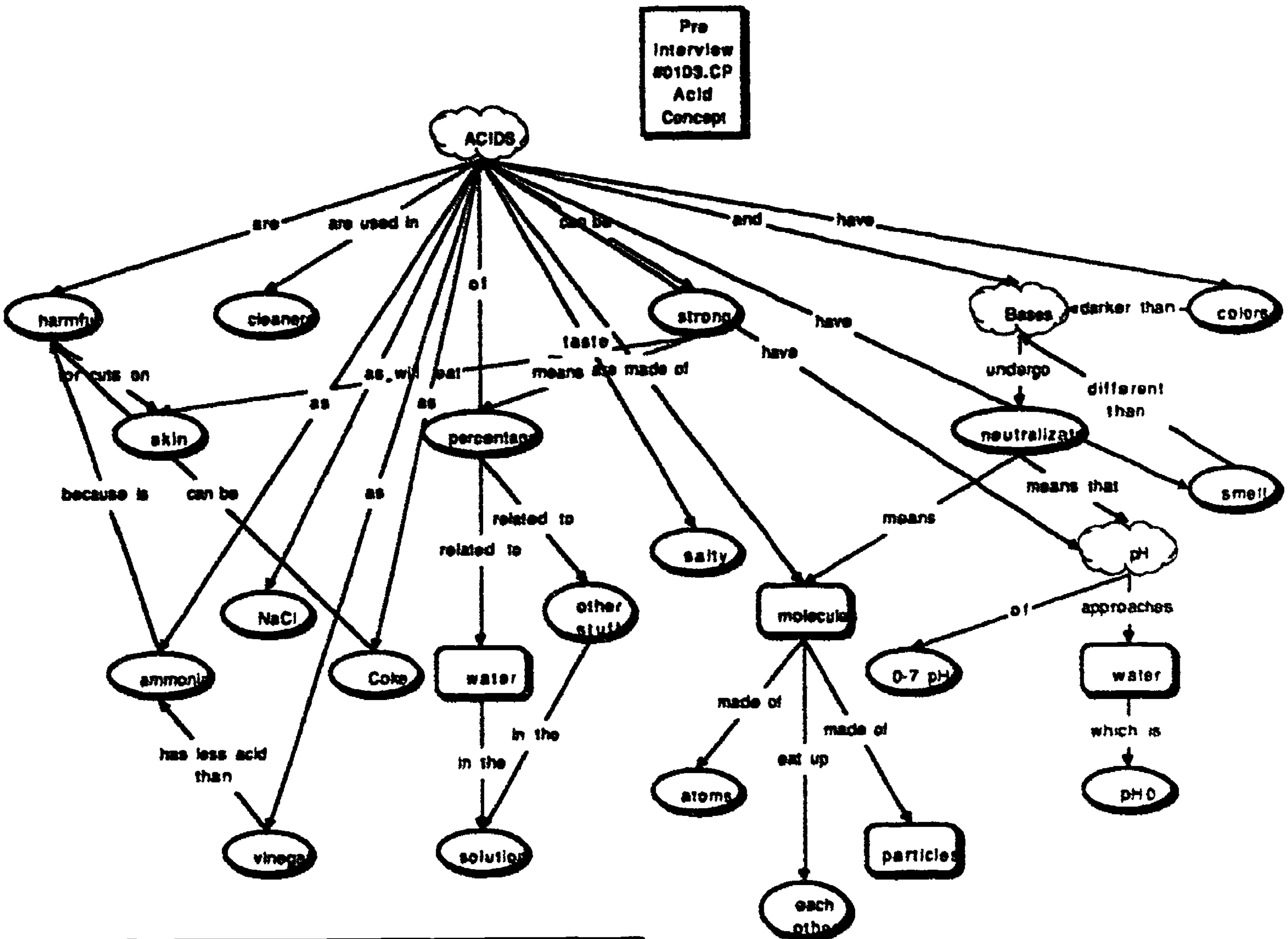

Figure 4. Pretreatment acid concept for #0103.CP, chemical indicator group.

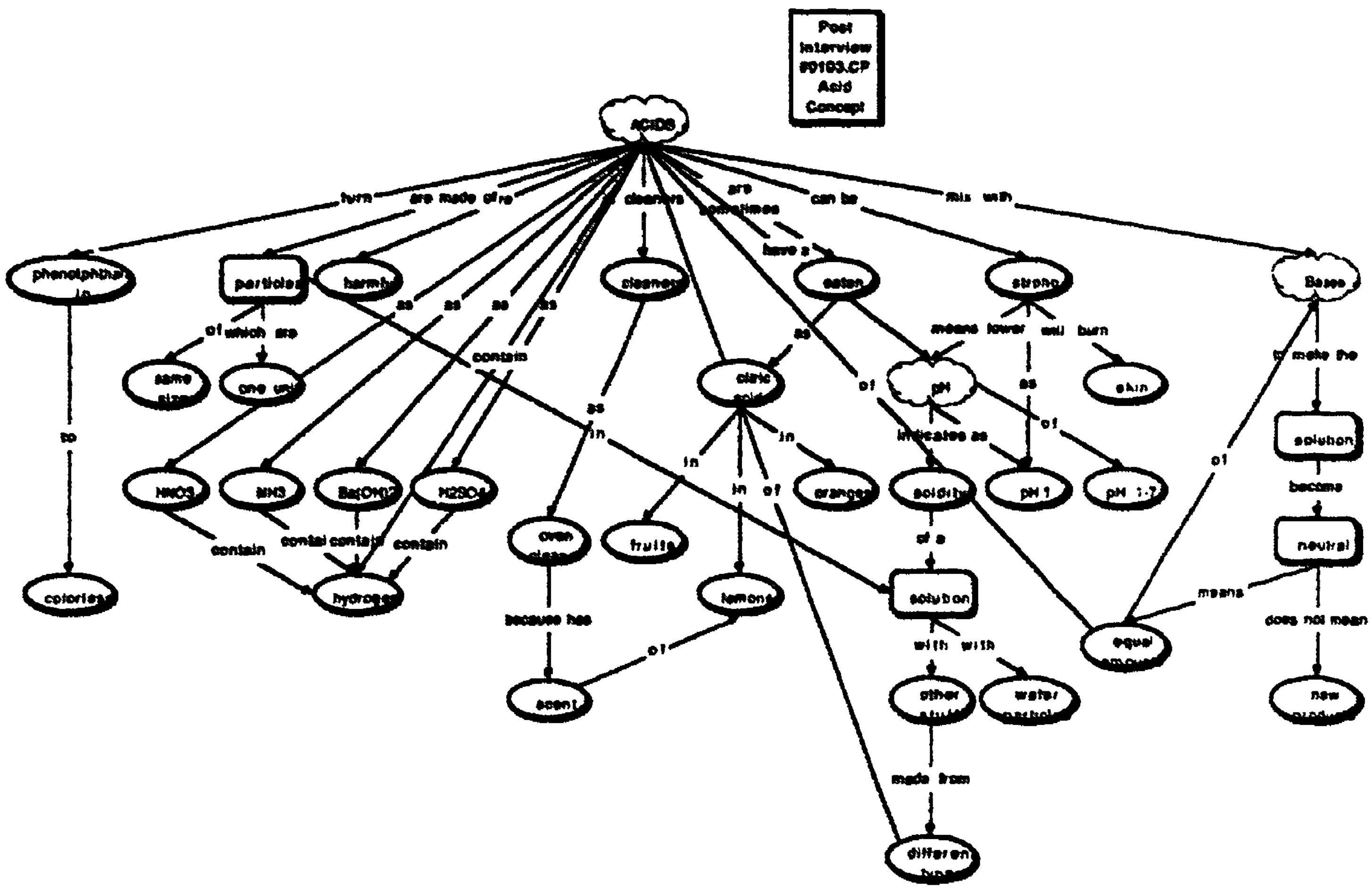

Figure 5 Posttreatment acid concept map for #0103 CP, chemical indicator group.

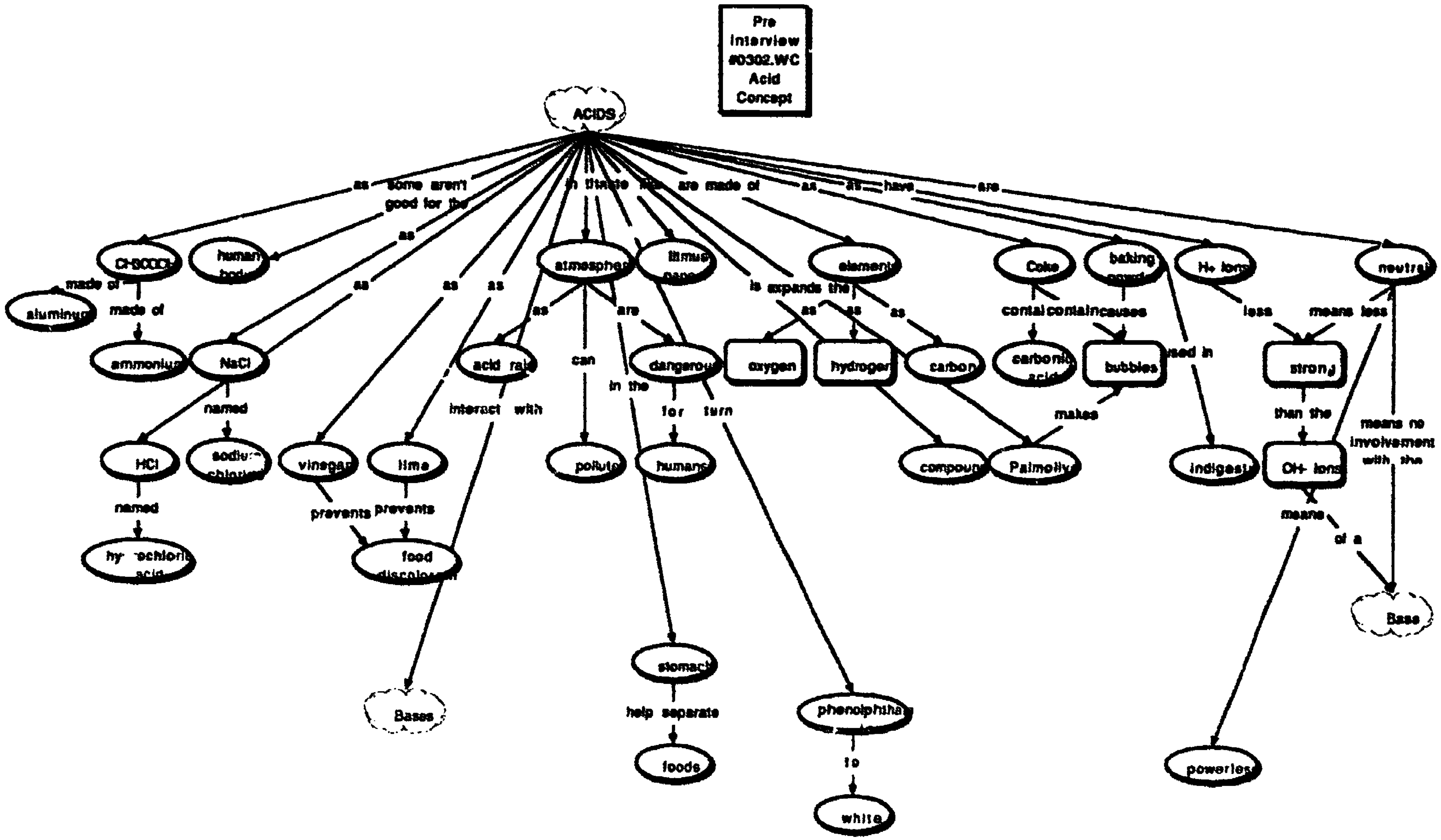

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Figure 6. Pretreatment acid concept for #0302.WC, microcomputer group.

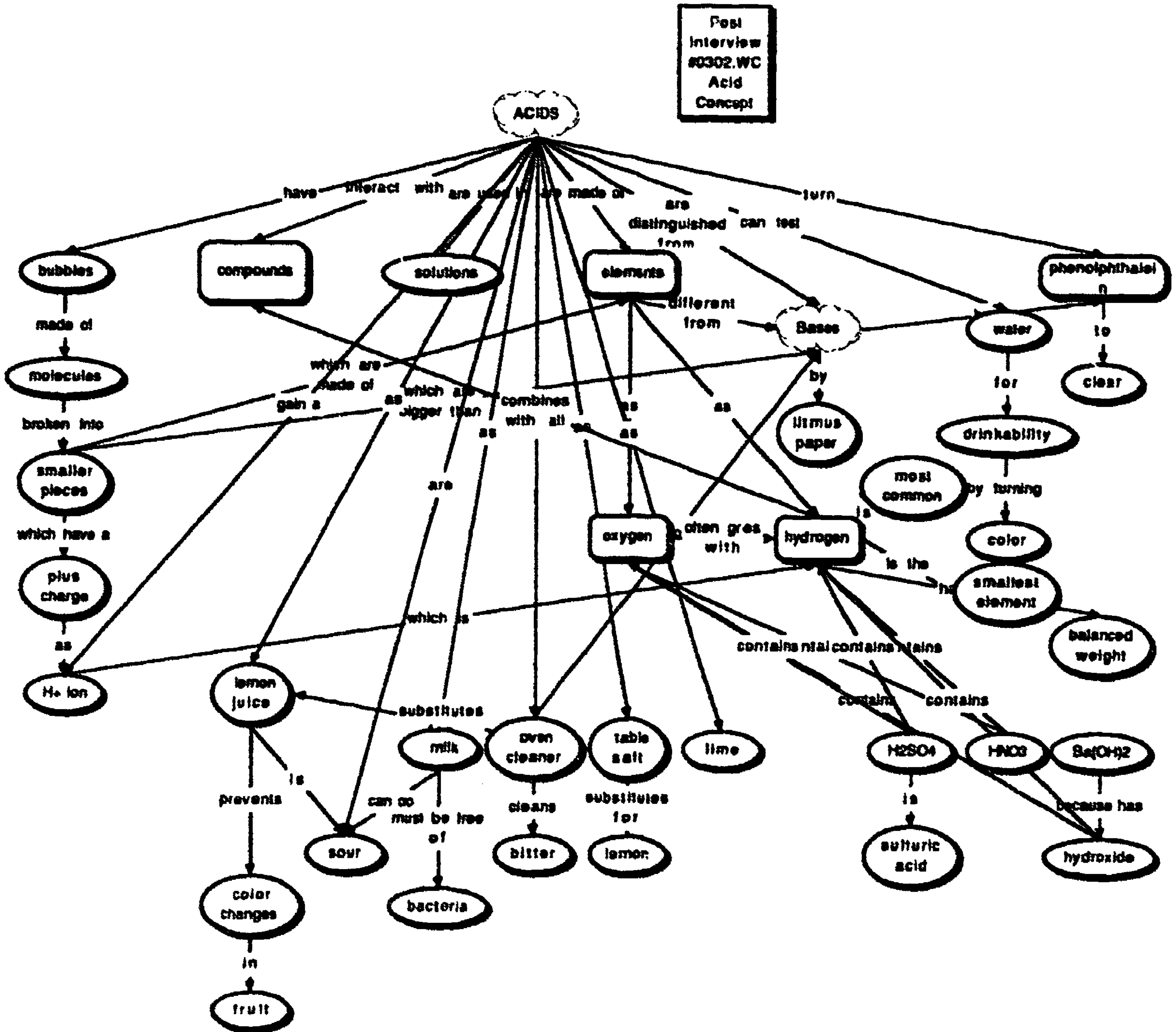

Figure 7. Posttreatment acid concept for #0302.WC, microcomuter group.

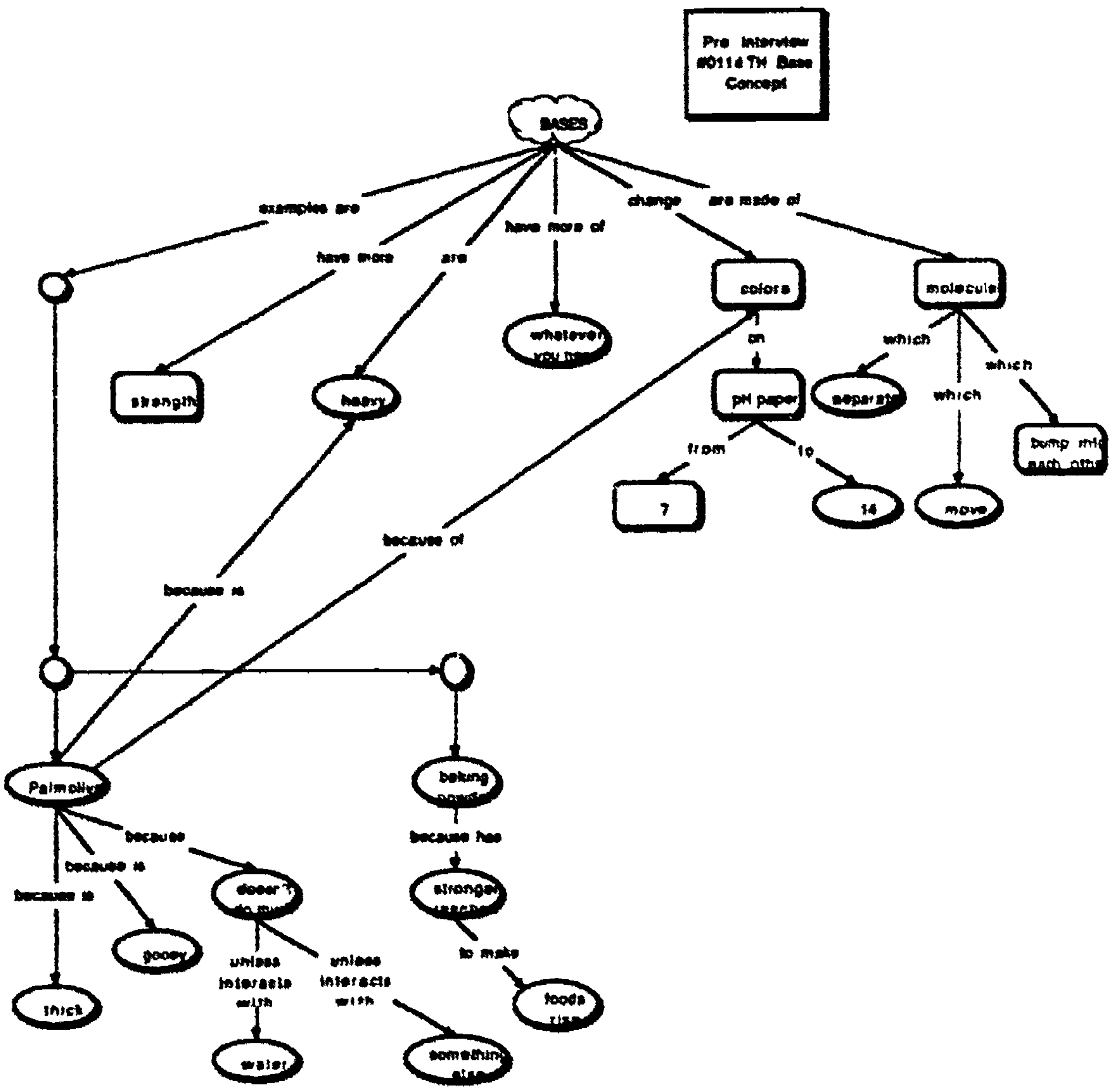

Figure 8 Preassessment base concept for #0114 TH, chemical indicator group

Post Interview #0114.TH Base Concept

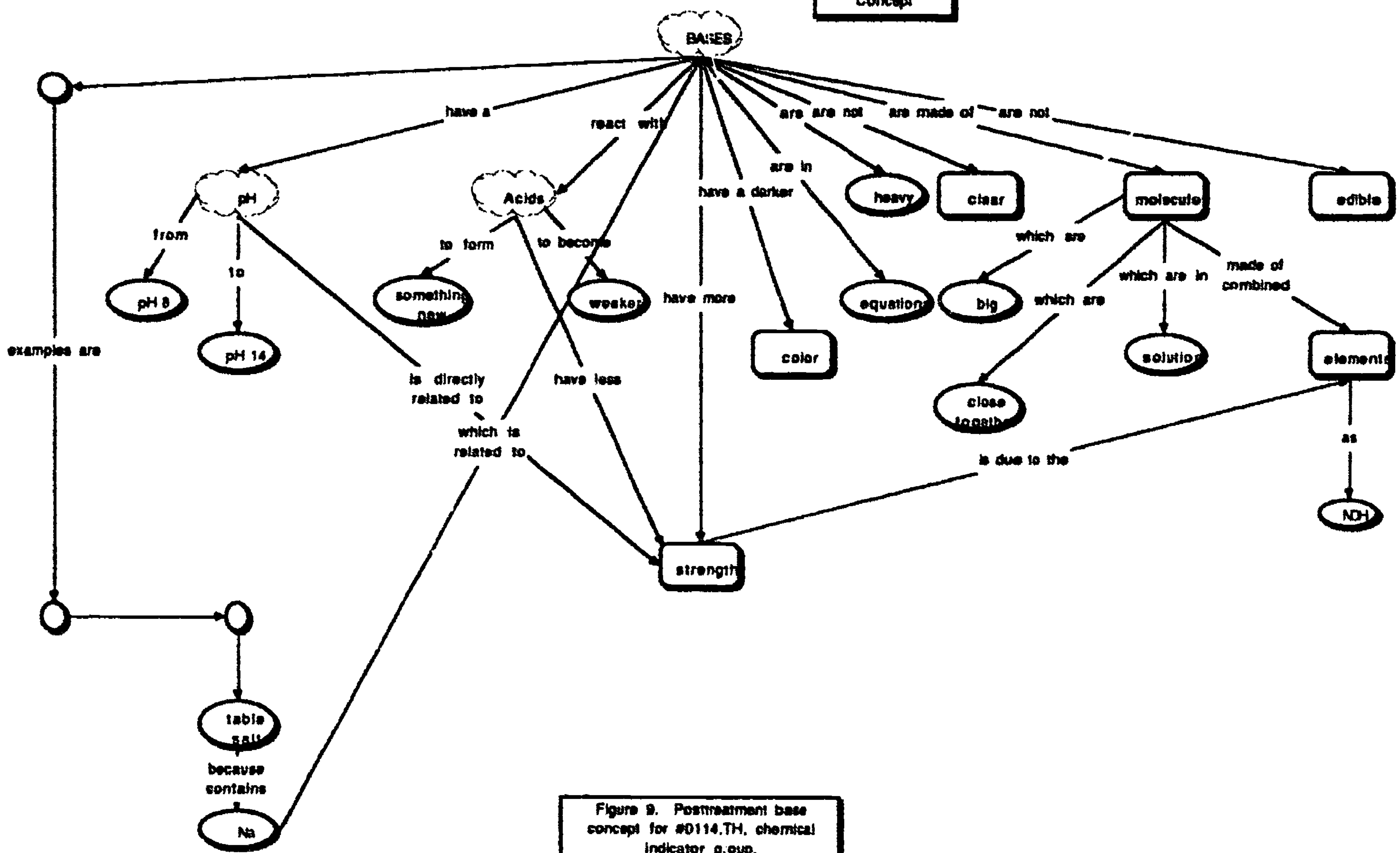

Figure 9. Posttreatment base concept for #0114.TH, chemical indicator group.

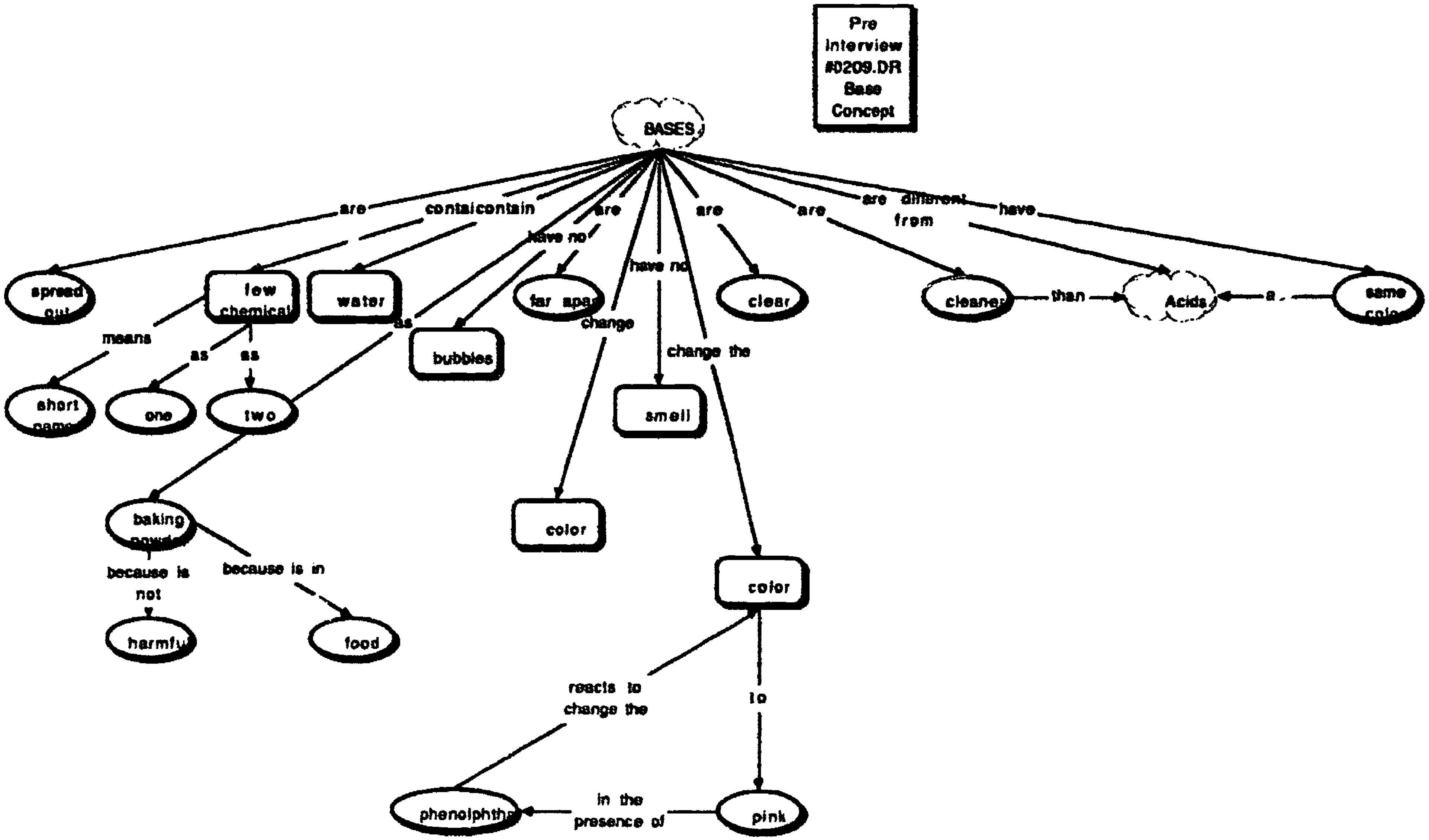

Figure 10. Pretreatment base concept for #0209.DR, pH meter group.

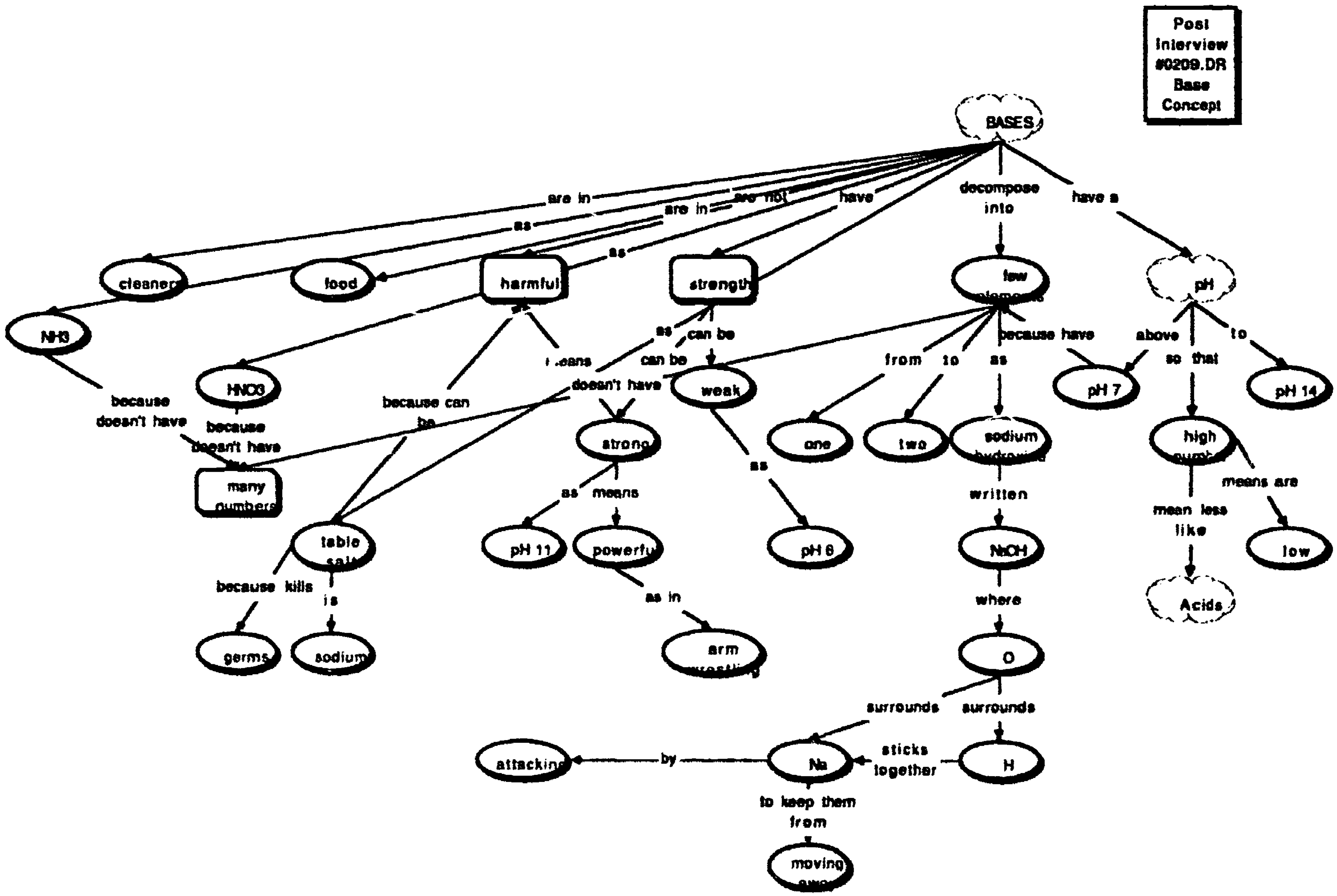

Figure 11. Posttreatment base concept for #0209.DP, pH meter group.

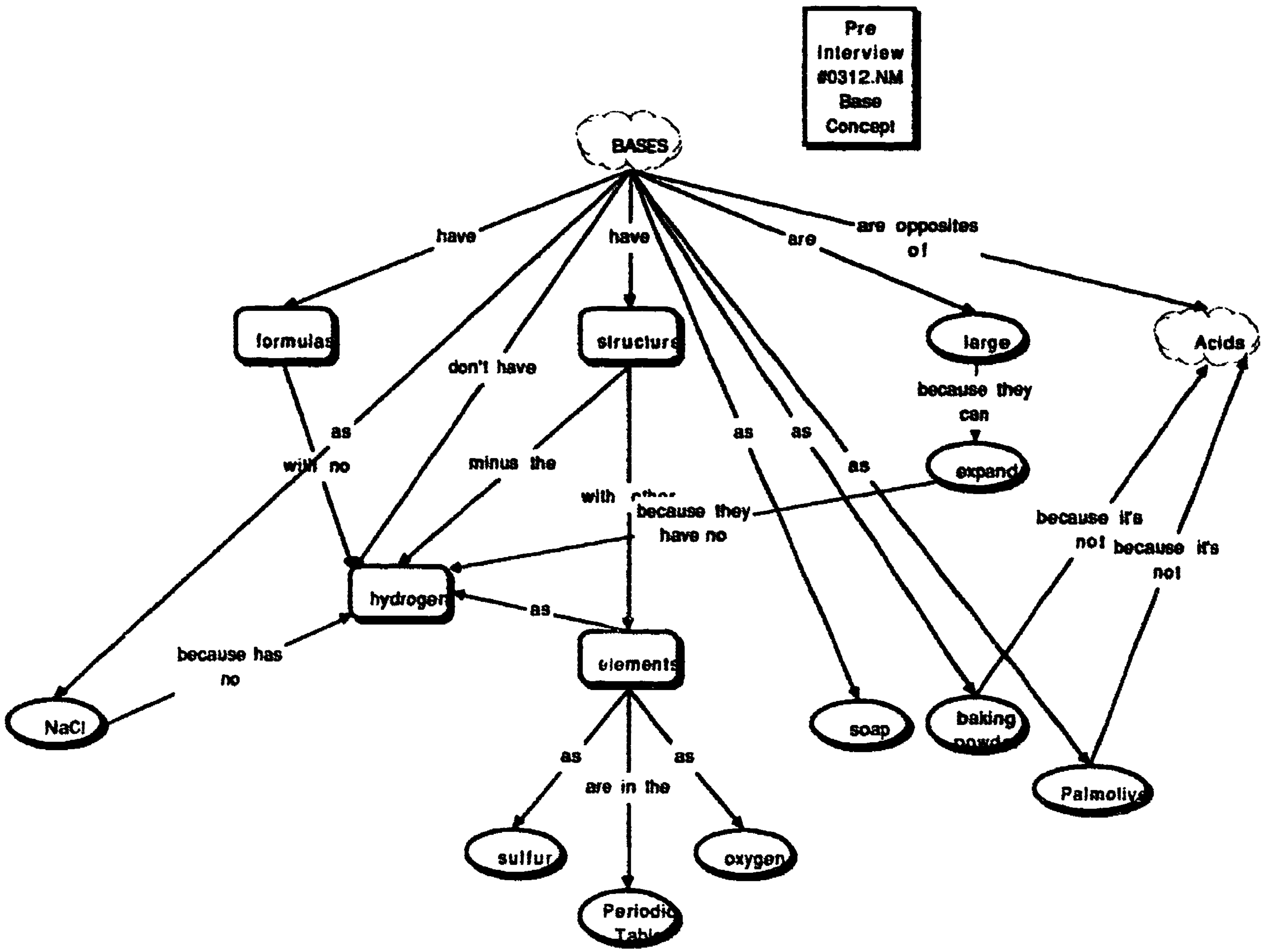

Figure 12. Pretreatement base concept for #0312.NM, microcomputer group.

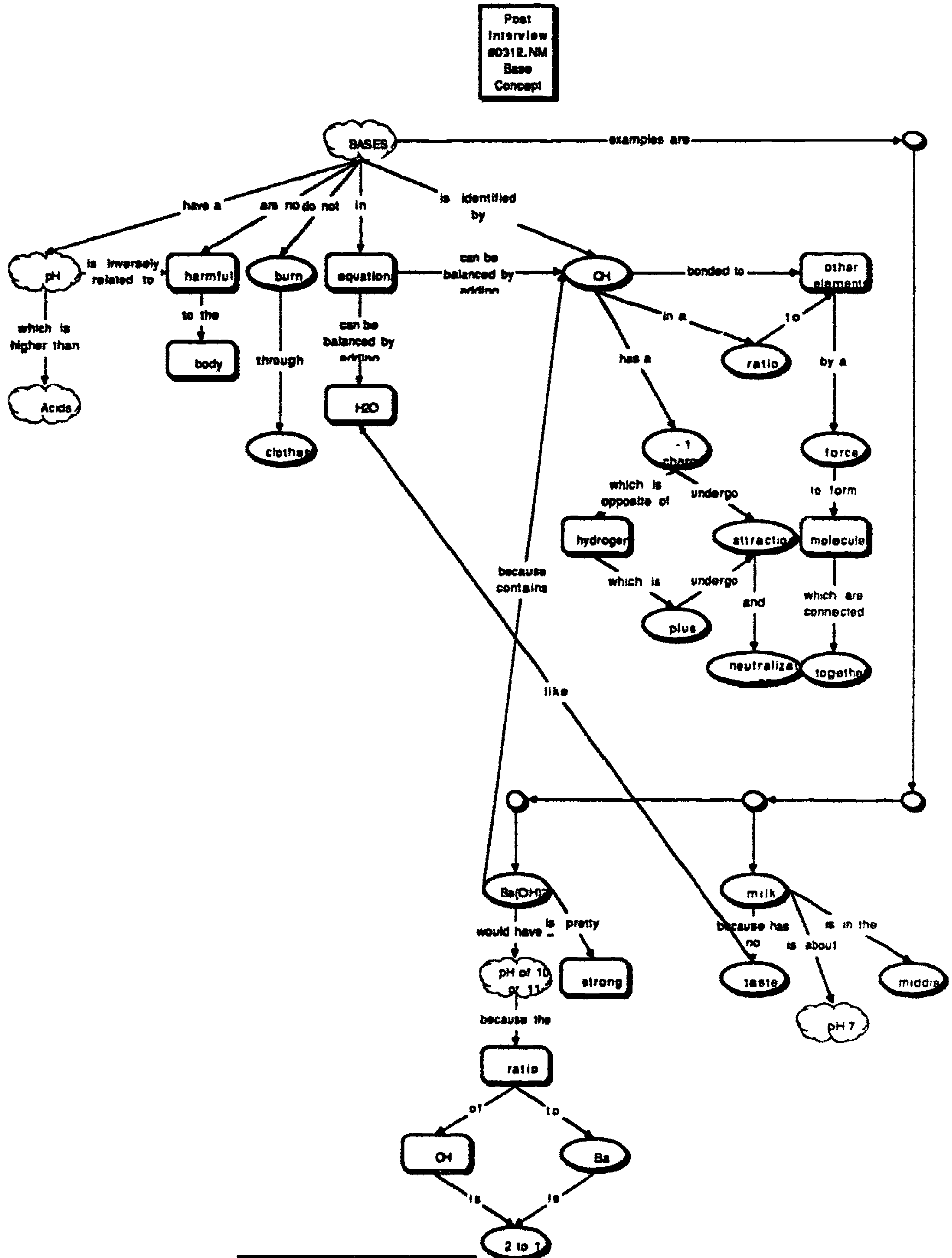

Figure 13. Posttreatment base concept for #0312.NM, microcomputer group.

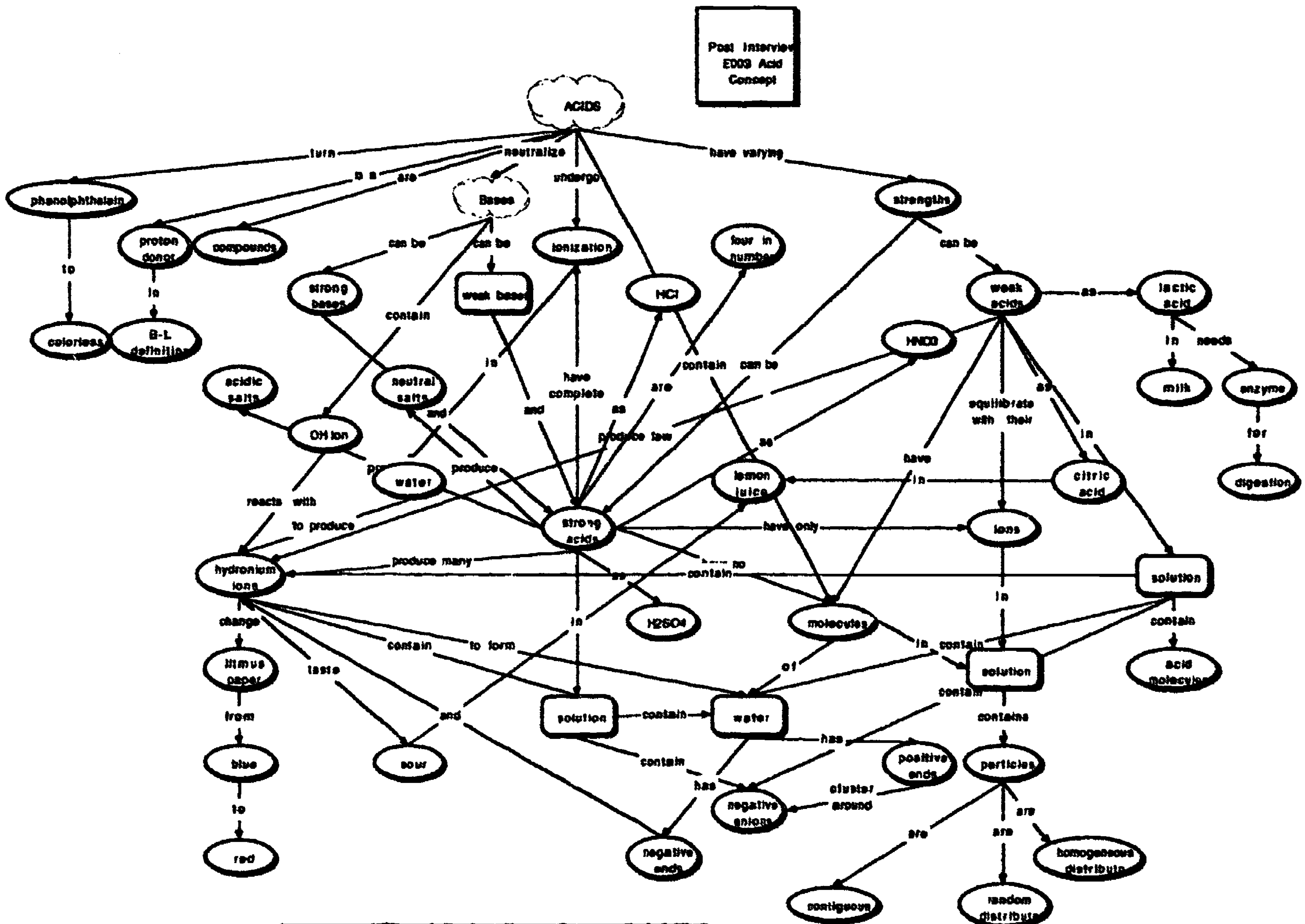

Figure 14 An expert's concept map of acids showing critical nodes.

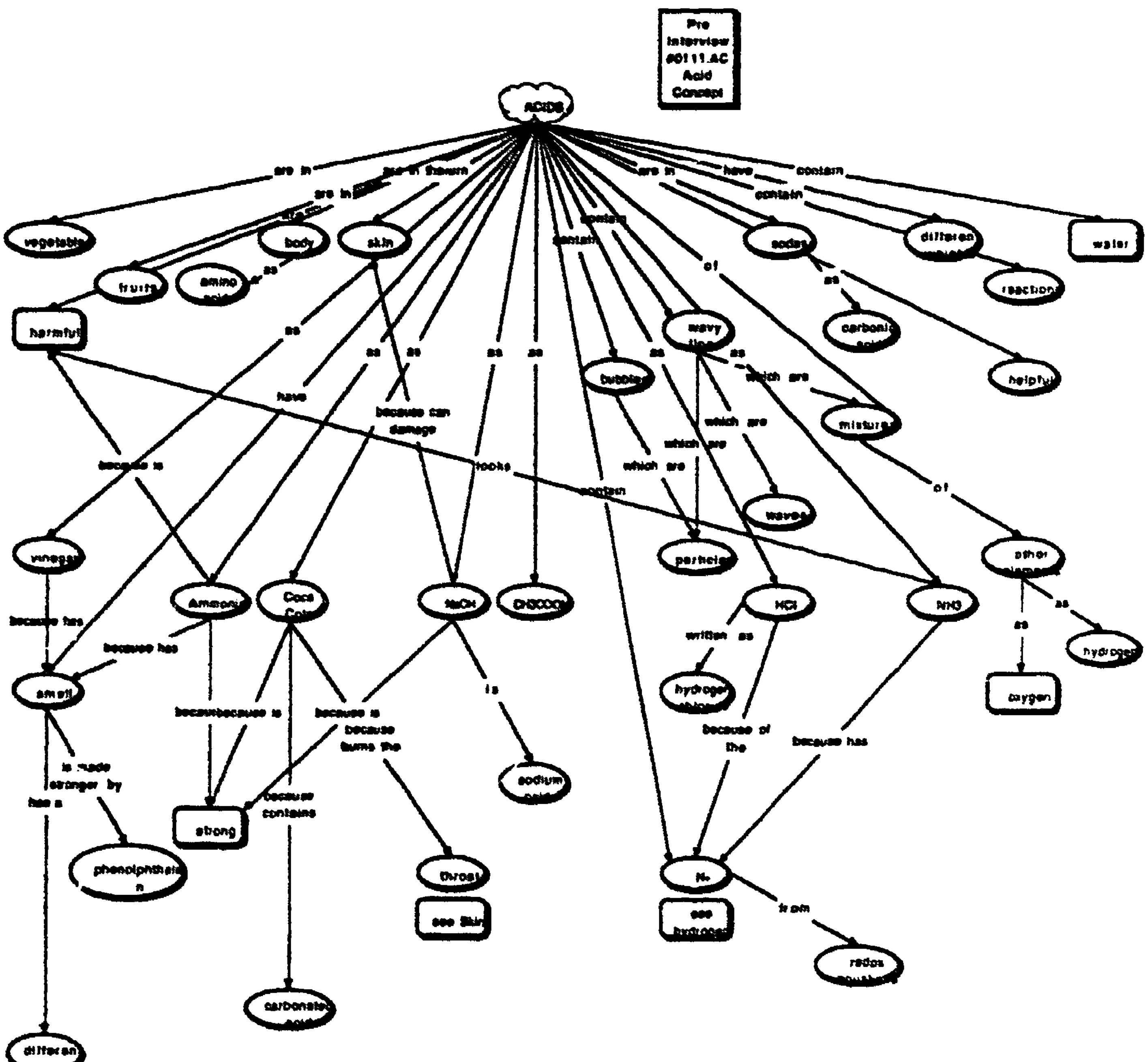

Figure 15. Pretreatment acid concept map for #0111 AC, chemical indicator group.

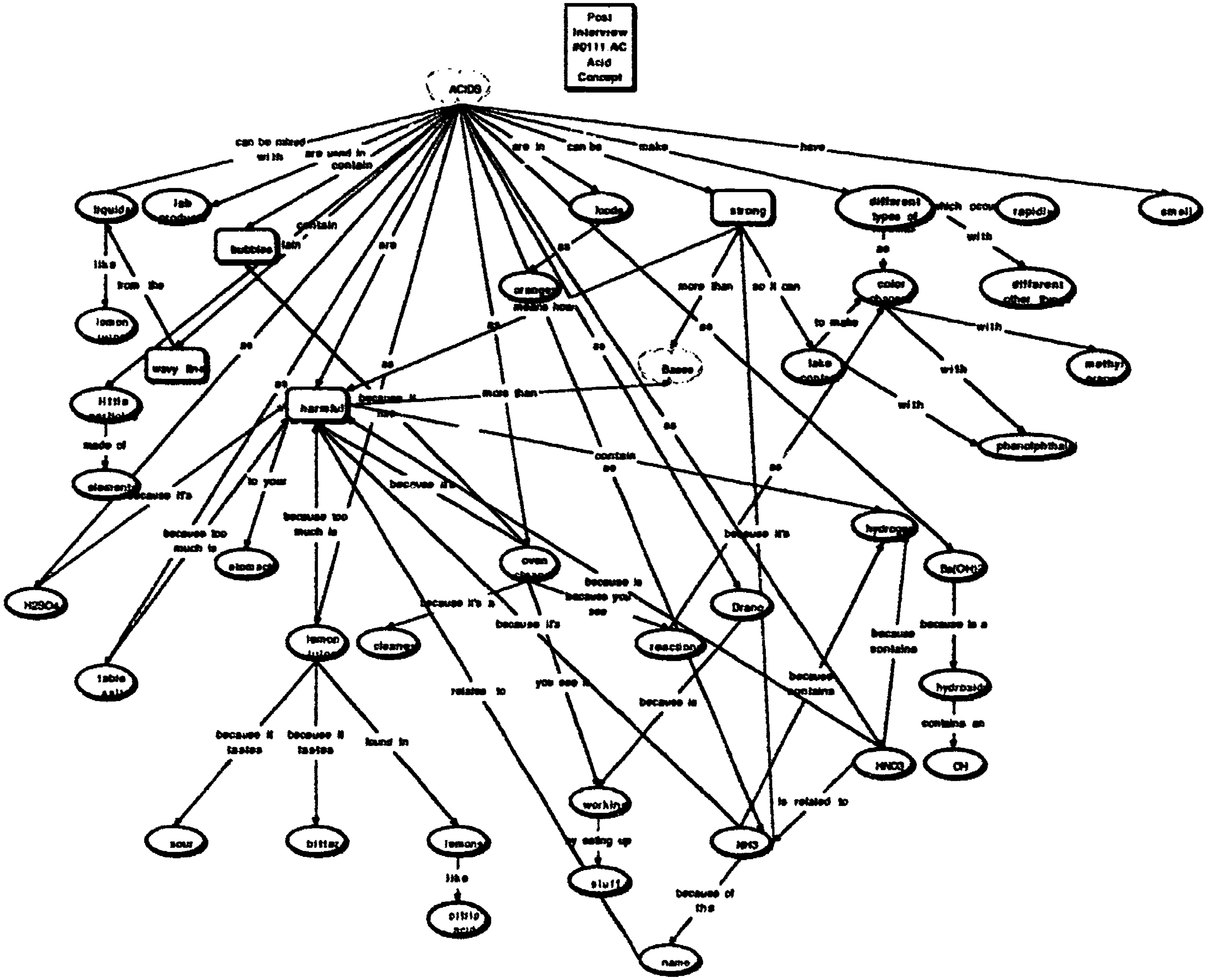

Figure 15 Posttreatment acid concept map for #0111 AC, chemical indicator group

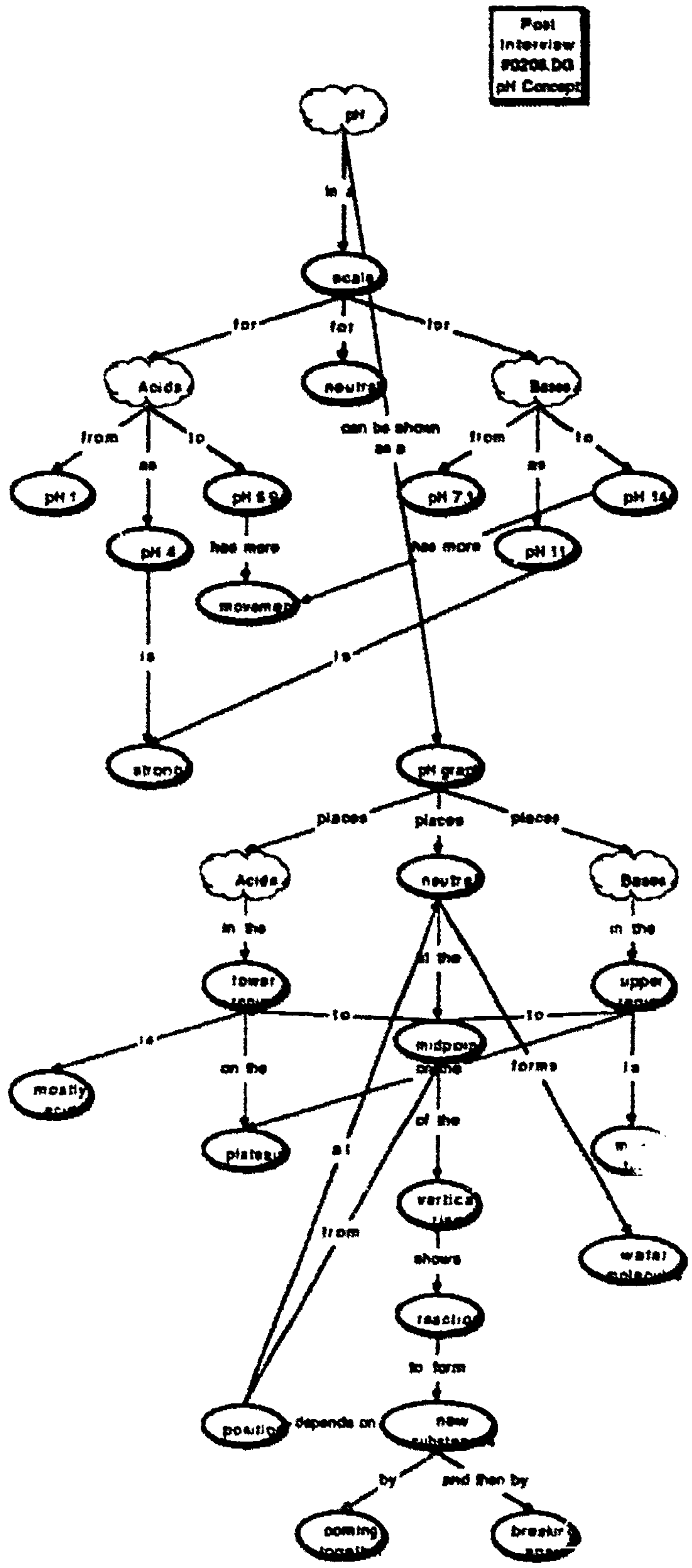

Figure 17. Posttreatment pH concept map for #0206 DG, pH meter group.

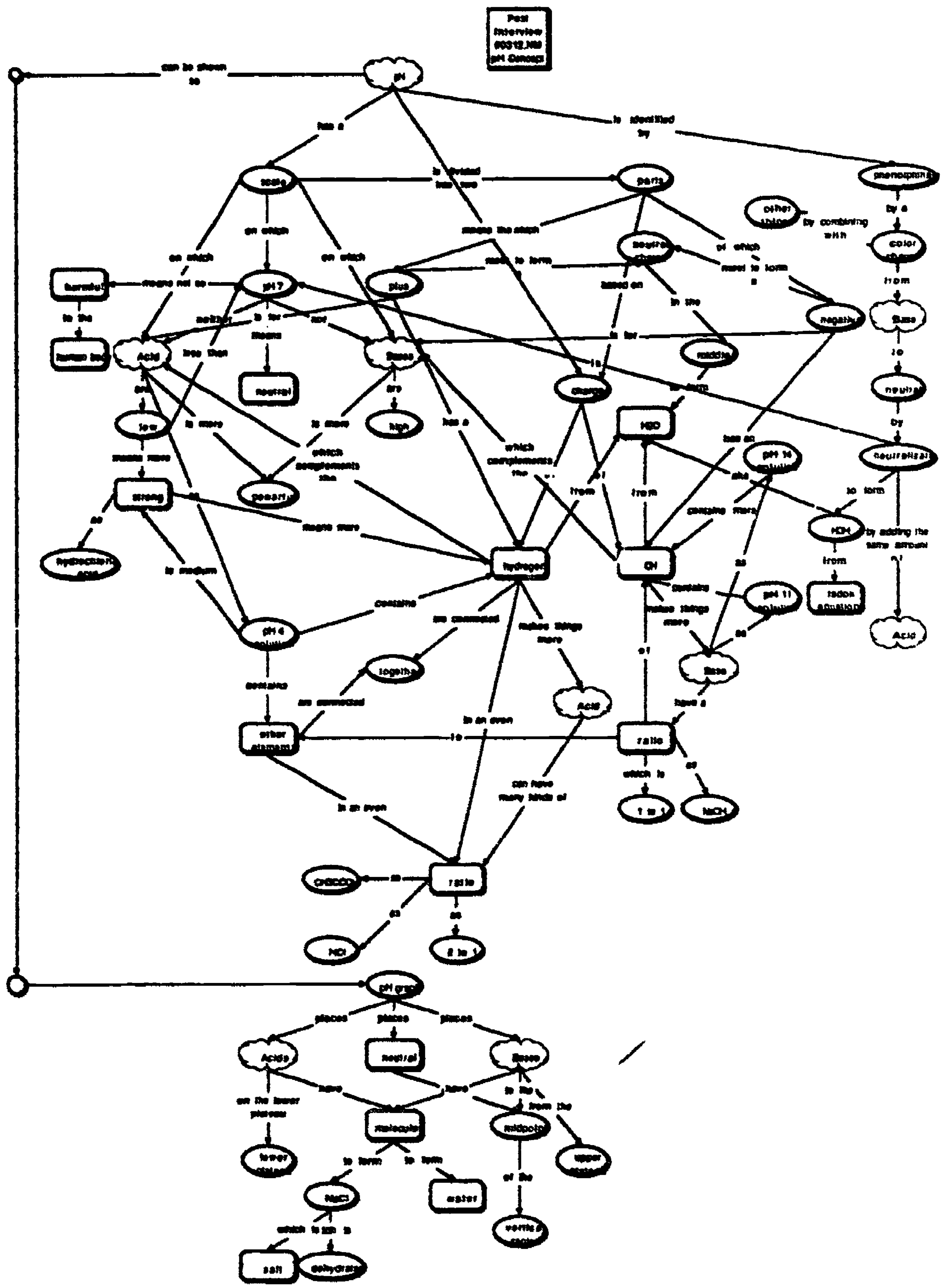

Figure 13. Posttreatment pH concept for #0312.NM, microcomputer group