Scientific Inquiry Model

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Scientific Inquiry as Discovery of Evidence, Hypotheses, and Arguments

Figure 1 illustrates the computational model of scientific inquiry which is at the basis of sInvestigator. When the students and sInvestigator address a specific inquiry (for example: *What type of organism is Euglena?*) they first use *abductive (imaginative) reasoning*, which shows that something is *possibly* true, to hypothesize possible answers:

- Euglena is a plant.
- Euglena is an animal.
- Euglena is another type of organism, neither plant nor animal.

They will need to analyze each of these hypotheses to determine which one is true. For this, they use each hypothesis to discover relevant evidence. One approach is to ask the question: *What evidence would be observable if this hypothesis were true?* The reasoning might go as follows: If H_k were true then the sub-hypotheses H_{k1} and H_{k2} would also need to be true. But if H_{k1} were true then one would need to observe evidence E_{k1}, and so on. This process leads to the discovery of new evidence by identifying the necessary conditions for hypothesis H_k.

A broader question that may guide the discovery of evidence is: *What evidence would be for or against this hypothesis?* In this case one would look for both favoring and disfavoring arguments for the hypothesis H_k to be true. They decompose each hypothesis into simpler and simpler

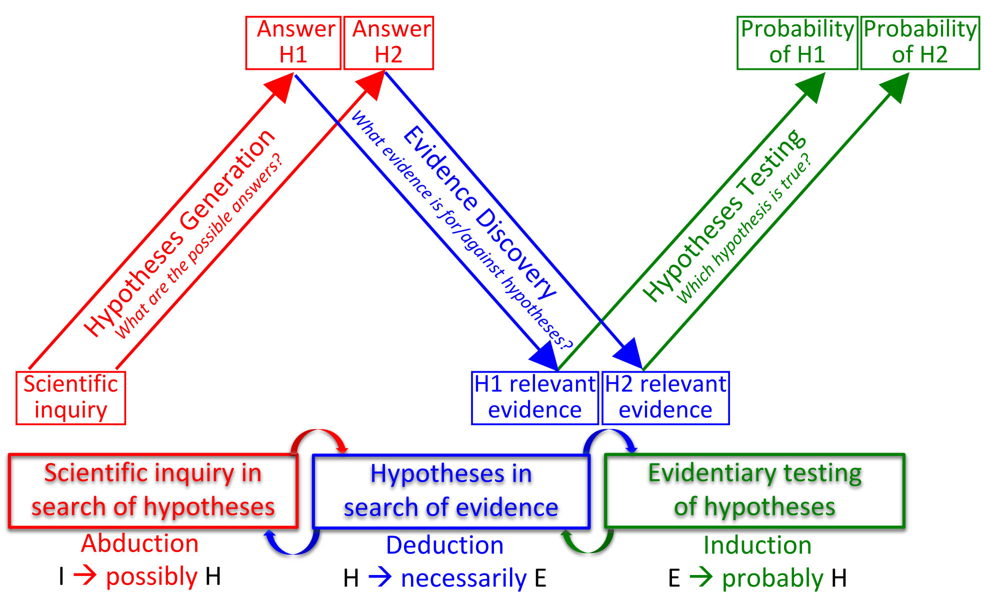

Figure 1. Scientific inquiry as discovery of evidence, hypotheses, and arguments.

hypotheses by considering favoring arguments (under the left, green square) and disfavoring arguments (under the right, pink square), as illustrated in Figure 2.

Favoring argument: IF "Euglena has plant features" THEN "Euglena is a plant"
Disfavoring argument: IF "Euglena has animal features" THEN "Euglena is not a plant"

The sub-hypotheses are further decomposed until the resulting leaf hypotheses are simple enough to point to what evidence would favor or disfavor each of them:

Favoring argument: IF "Euglena synthesizes nutrients by photosynthesis" and "Euglena feeds by autotrophy"
THEN "Euglena has plant features"

Search for evidence to determine whether Euglena synthesizes nutrients by photosynthesis.
Search for evidence to determine whether Euglena feeds by autotrophy.

Finally the students test the hypotheses based on the credibility and relevance of the discovered evidence, and determine which one is true.

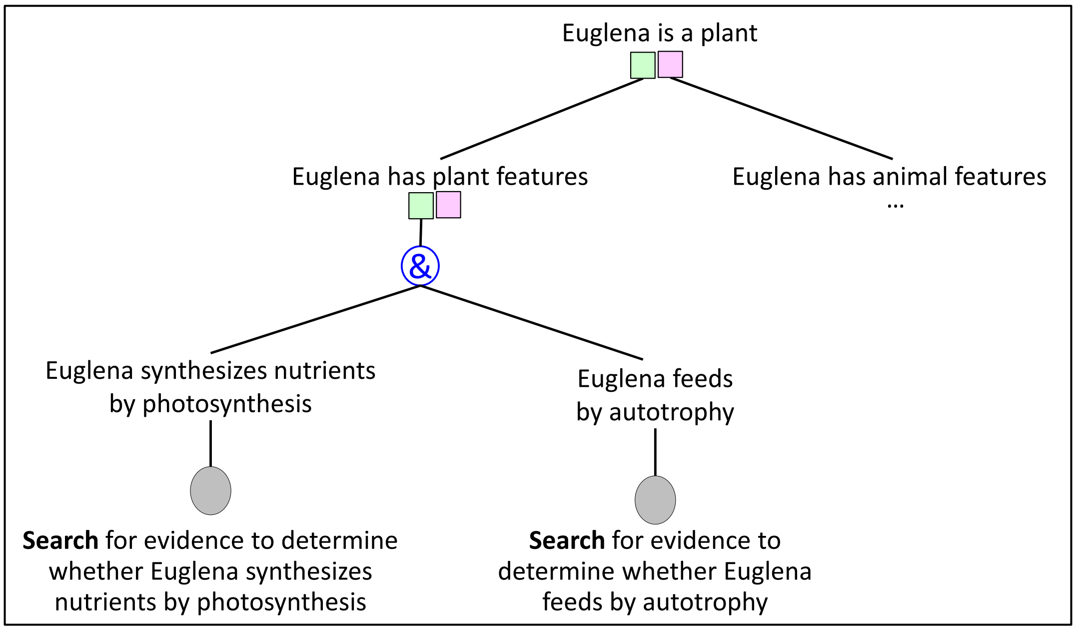

Figure 2. Hypothesis in search of evidence.

Generic Inquiry-based Teaching and Learning Experience

Figure 3 illustrates a generic inquiry-based teaching and learning experience with sInvestigator in the context of the "Energy sources" topic.

1. The instructor formulates an inquiry: What type of energy to produce?
2. The students hypothesize possible answers:
   Wind energy, Hydroelectric energy, Nuclear energy, Solar energy.

3. The students form teams, each team developing an evidence-based argumentation for assessing the probability of their selected hypothesized answer.
4. Each team considers arguments in favor and against the selected hypothesis:

   Wind energy
   Favoring argument: Low production costs – wind is free
   Disfavoring argument: Each wind turbine does not generate very much energy
5. The students search for evidence on the Internet and evaluate its relevance to the corresponding hypothesis, as well as its credibility:

   E1 Low cost of wind energy

   Wind energy is one of the cheapest sources of electricity, and it's getting cheaper, Robert Fares on August 28, 2017 in Scientific American.

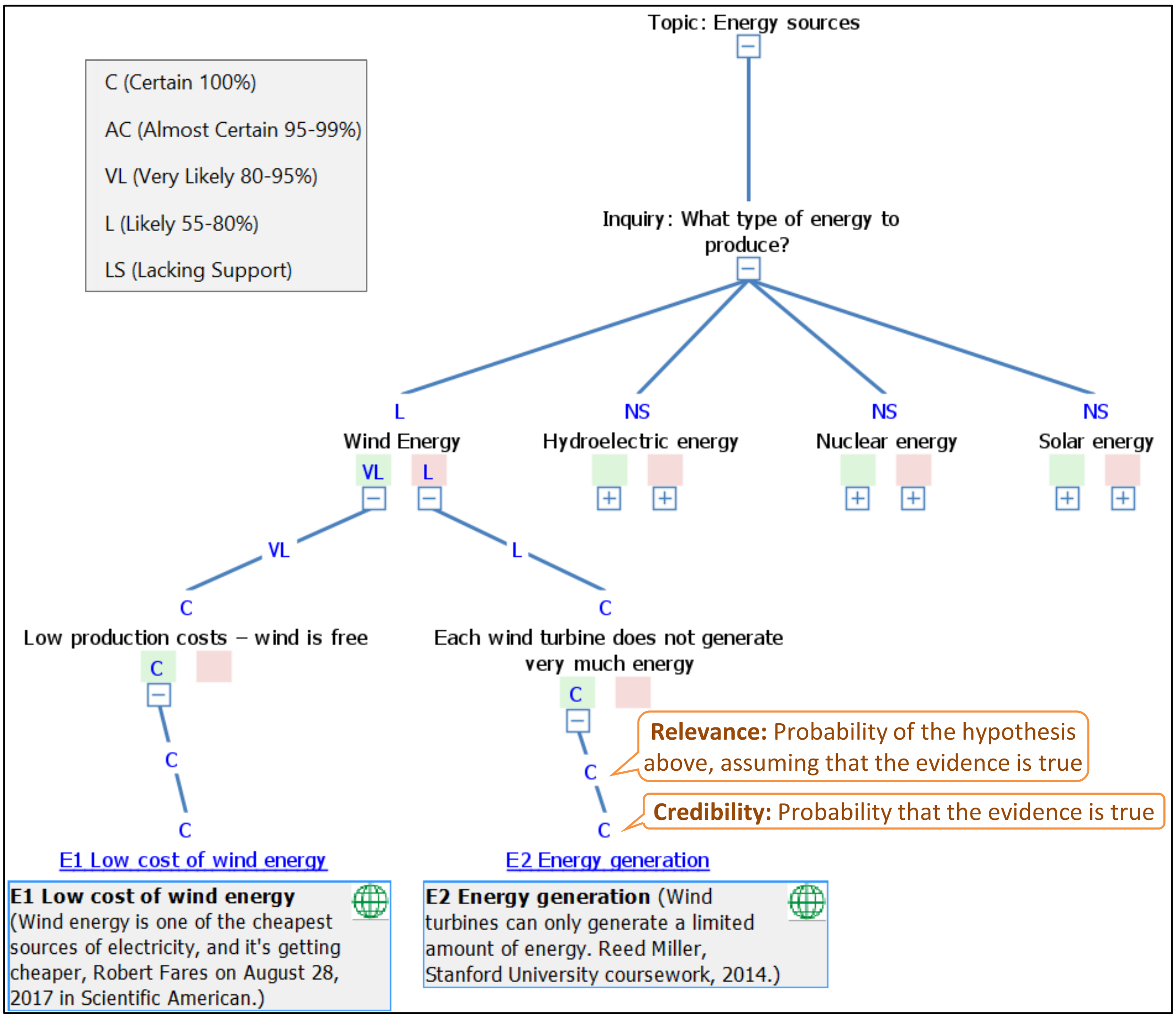

Figure 3. Generic inquiry-based teaching and learning experience.

https://blogs.scientificamerican.com/plugged-in/wind-energy-is-one-of-the-cheapest-sources-of-electricity-and-its-getting-cheaper/

Relevance: C (Certain 100%)

Credibility: C (Certain 100%)

6. sInvestigator assesses the probability of the hypotheses.
7. The teams present and debate their argumentations in class.

The next section presents a detailed example of using inquiry in classroom.

Sample Inquiry with sInvestigator in a Science Class

A classical textbook example of using inquiry in a science class is presented in *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*, pp.5-11, National Research Council, 2000, Washington, DC: The National Academies Press. https://doi.org/10.17226/9596.

The following is an adaptation of this example to show how sInvestigator can naturally support inquiry-based teaching and learning.

« Several of the students in Mrs. Graham's fifth grade science class were excited when they returned to their room after recess one fall day. They pulled their teacher over to a window, pointed outside, and said, *we noticed something about the trees on the playground. The left one has lost all its leaves, the middle one has multicolored leaves — mostly yellow — while the right one has lush, green leaves. Why are those trees different? They used to look the same, didn't they?* Mrs. Graham didn't know the answer. But she knew that her class was scheduled to study plants later in the year, and this was an opportunity for them to investigate questions about plant growth that they had originated and thus were especially motivated to answer. Although she was uncertain about where her students' questions would lead, Mrs. Graham chose to take the risk of letting her students pursue investigations with the assistance of sInvestigator. *Let's use sInvestigator to make a list of hypotheses that might explain what's happening to those trees outside.* They used sInvestigator to specify the topic of study, the inquiry, and the following list of competing explanatory hypotheses (see Figure 4):

- It must be too much water that causes a tree to die.
- Insects are eating two of the trees.
- The trees have different ages.

Mrs. Graham then invited each student to pick one hypothesis which led to several groups, a "water" group, an "illness" group, and an "age" group. She asked each group to use sInvestigator in order to plan and conduct a simple investigation to test their preferred hypothesis.

For the next three weeks, science periods were set aside for each group to carry out its investigation. Each group used sInvestigator to conduct its investigation, discovering a variety of sources with information about characteristics of trees, their life cycles, and their environments.

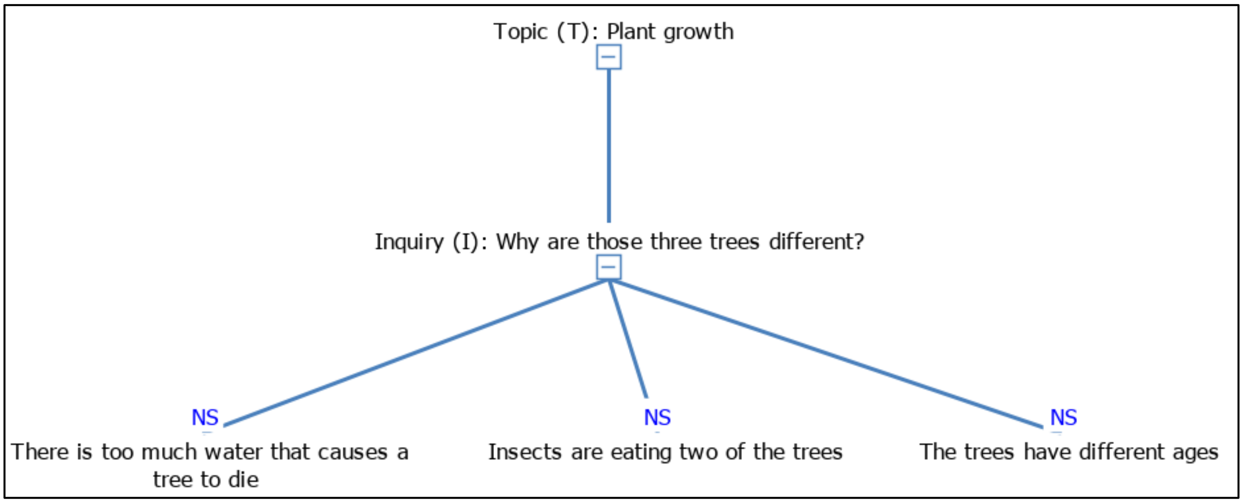

Figure 4. Topic, inquiry, and possible answers.

Let us consider the water group that investigated the hypothesis "There is too much water that causes a tree to die." They decomposed this hypothesis into two simpler hypotheses that showed more clearly what evidence may be used to test it (see Figure 5):

- There is too much water at the root of the dying tree.
- Too much water at the root causes the tree to die.

To discover evidence for the first sub-hypotheses, the water group decided to look at the ground around the trees every hour that they could. They took turns on making individual observations and since some of them lived near the school, their observations continued after school hours and on weekends. Even though they missed some hourly observations, they had sufficient data indicating that there is too much water at the root of the dying tree. They introduced this information into sInvestigator, naming it E1 Water observations, as shown in the right hand side of Figure 5. Then they dragged it on the left (green) square under the "There is too much water at the root of the dying tree" sub-hypothesis, to indicate that this is favoring evidence for it.

Now the water group can assess the probability of the "There is too much water at the root of the dying tree" hypothesis based on E1 Water observations, by using the following symbolic probability scale (shown also in the upper-left of Figure 9):

LS (Lacking Support) < L (Likely 55-80%) < VL (Very Likely 80-95%) <
< AC (Almost Certain 95-99%) < C (Certain 100%)

In this scale, the considered hypothesis may be "Lacking Support" from evidence, or the evidence may indicate some level of support, such as "Very Likely 80-95%." Each symbolic probability value (e.g., "Very Likely") is abbreviated ("VL") in the sInvestigator analysis whiteboard in order to reduce space usage and facilitate the visualization of larger argumentations.

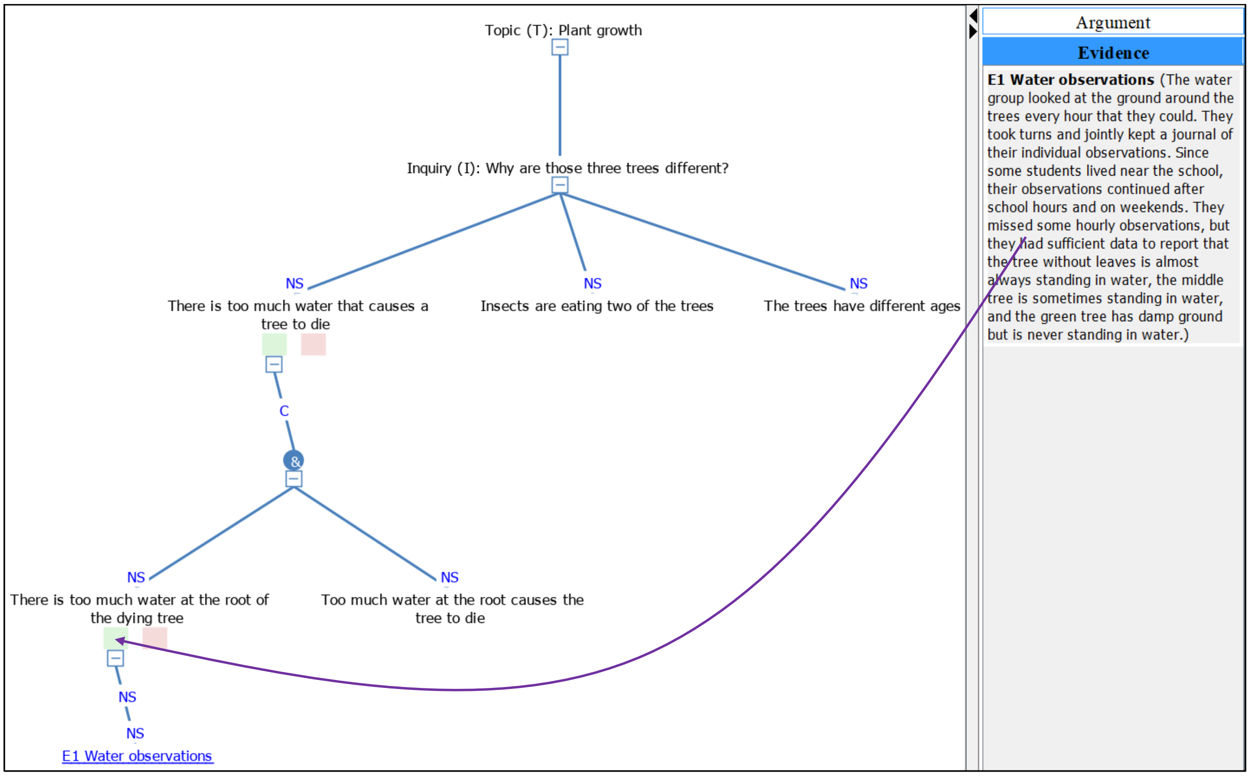

Figure 5. Hypotheses in search of evidence

To assess the probability of a hypothesis based on an item of evidence, the water group has to first assess the *credibility* and the *relevance* of evidence. Then sInvestigator determines the *inferential force* of evidence and *probability* of hypothesis, as illustrated in Figure 6.

The *credibility* of the evidence item E1 Water observations is obtained by answering the question: *What is the probability that the evidence is true?* The students' answer was AC (Almost Certain 95-99%) since a few data points were missing and, on rare occasions, the tree was not standing in the water. This justification was entered into sInvestigator, as shown in the bottom-right of 6.

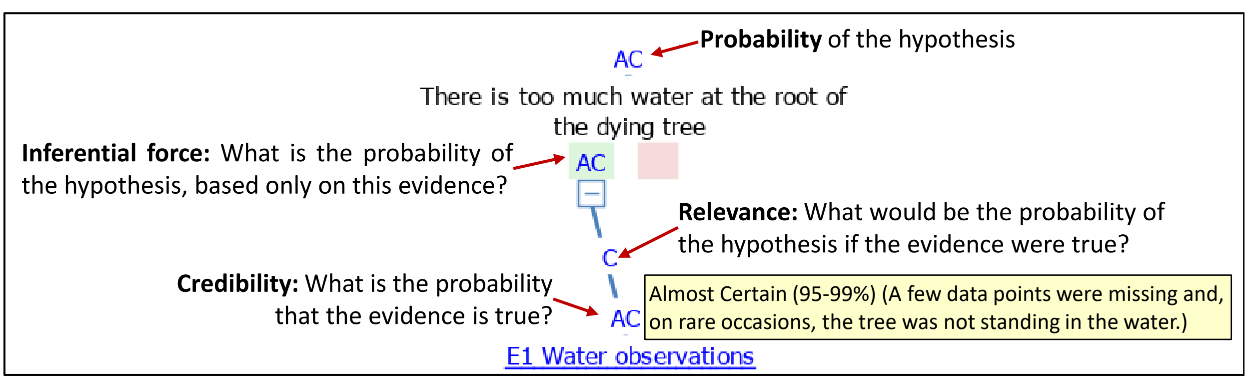

Figure 6. The credentials of evidence.

The *relevance* of the evidence item E1 Water observations is obtained by answering the question: *What would the probability of the hypothesis be if the evidence were true?* The students' answer was certain (C). Indeed, if the evidence item is true then the hypothesis is true.

The *inferential force* of the evidence item on the hypothesis answers the question, *"What is the probability of the hypothesis, based only on this evidence?"* Obviously, an irrelevant item of evidence will have no inferential force, and will not convince us that the hypothesis is true. An item of evidence that is not credible will have no inferential force either. Only an item of evidence that is both very relevant and very credible will convince us that the hypothesis is true. Consistent with both the Baconian and the Fuzzy min/max probability combination rules (Cohen, 1977, pp.167-187; Zadeh, 1965, pp.340-341; Schum, 1979, pp.460-463), the inferential force of an item of evidence on a hypothesis is determined as the minimum between its credibility and its relevance which, in this illustration, is AC (Almost Certain 95-99%).

Because, in this case, we have only one item of evidence, its inferential force on the hypothesis is also the *probability* of the hypothesis.

Concerning the sub-hypothesis "Too much water at the root causes the tree to die," one of the students recalled that several months ago the leaves on one of his mother's geraniums had begun to turn yellow. She told him that the geranium was getting too much water. This item of information was represented in sInvestigator as the item of evidence E2 Geranium case, favoring the hypothesis. The students agreed to assess its credibility as AC (Almost Certain 95-99%) because, although the mother has experience with plants, she is not a professional. They assessed the relevance as VL (Very Likely 80-95%) because geraniums is a different type of plant. As a result, sInvestigator assessed the inferential force of E2 Geranium case as VL (Very Likely 80-95%). Additionally, the students searched the Internet and found the article "We Had Plenty of Rain; Why Are My Trees Dying?" by Sheila Dunning from the University of Florida, stating that a saturated soil may result in the death of the tree. The students conducted a deeper credibility analysis by assessing author's competence (affiliation and history), objectivity (relationship to current knowledge and conflict of interest), and publication's reputation, and sInvestigator computed the credibility as C (Certain 100%). The relevance was also assessed as C (Certain 100%), leading sInvestigator to assess its inferential force as C (Certain 100%). Additionally, sInvestigator assessed the inferential force of all favoring evidence (i.e., both E2 Geranium case and E3 Saturated soil) as C (Certain 100%), by taking the maximum of their inferential forces. This is also the probability of the hypothesis "Too much water at the root causes the tree to die" because no disfavoring evidence was found. However, if any disfavoring evidence would have been found, then sInvestigator would have determined whether, on balance, the totality of evidence favors or disfavors the hypothesis, and to what degree.

Having assessed the probability of "There is too much water at the root" as AC (Almost Certain 95-99%), and that of "Too much water at the root causes the tree to die" as C (Certain 100%), sInvestigator inferred the probability of their top-level hypothesis "There is too much water at the root that causes a tree to die" as AC (Almost Certain 95-99%). This is the minimum between these probabilities and the joint relevance of the two sub-hypotheses, which is C (Certain 100%) (see the left part of Figure 7).

The “illness” group searched for insects on the trees. Some ants were noticed on all the trees, but without any significant difference between the trees to justify why one of the trees was dying because of them. This information was entered as evidence item E4 Some ants on all trees, disfavoring the hypothesis that “Insects are eating one of the trees.” Therefore sInvestigator concluded that there is no support for this hypothesis (see Figure 7).

Similarly, the “age” group answered their question fairly quickly. They contacted the PTA members who were involved in planting that part of the playground and found the original receipts for the purchase of the trees. A check with the nursery indicated that all three trees were identical and of approximately the same age when purchased.

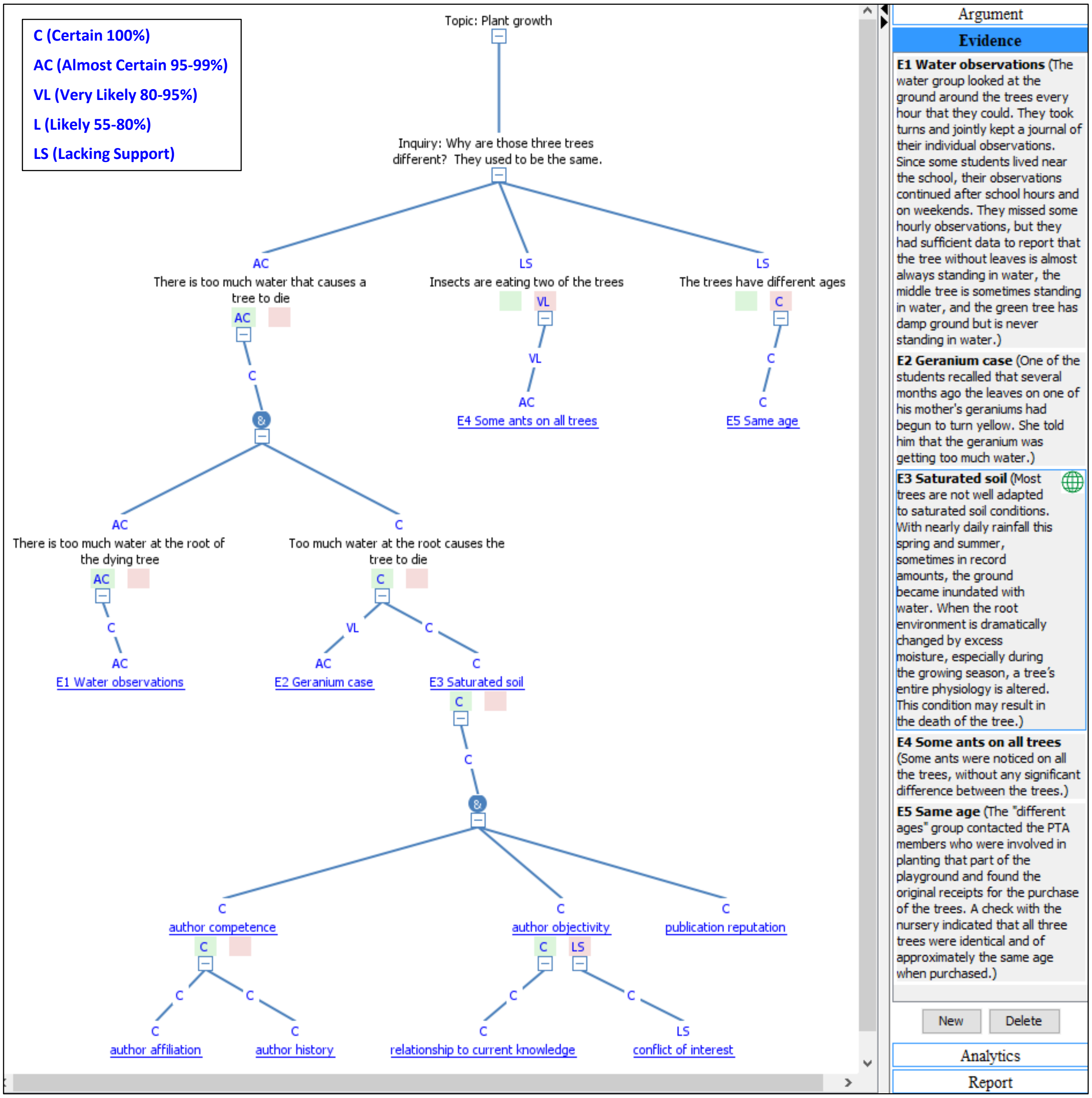

Figure 7. Hypotheses testing.

Finally, sInvestigator automatically generated a report for each group, describing the analysis logic, citing sources of data used, and the manner in which the analysis was performed. These reports were further edited by the groups before being presented to the class.

As different groups presented and compared their analyses, the class learned that some evidence — such as that from the group investigating whether the trees have different ages — did not explain the observations. But the explanation that seemed most reasonable to the students, that fit all the observations and conformed with what they had learned from other sources, was “too much water.” After their three weeks of work, the class was satisfied that together they have found a reasonable answer to their question.