Inquiry-based Teaching of Critical Thinking Skills in Science with sInvestigator

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ABSTRACT

Inquiry-based teaching and learning is recognized as being very effective, but very difficult to use in practice. This report presents an inquiry-based approach to the teaching of critical thinking skills in science with an intelligent computer system called sInvestigator (science Investigator). sInvestigator helps students develop critical thinking skills in addressing scientific problems, through a rigorous yet easy to employ inquiry-based approach. The report first introduces the computational framework of scientific inquiry as discovery of evidence, hypotheses, and arguments, on which sInvestigator is based. Then it introduces the features of sInvestigator with a couple of illustrative examples, a generic inquiry-based teaching and learning exercise and a specific one. Finally it presents a variety of inquiry-based exercises for use in science classes from middle school through university.

1. Introduction

Significant progress has been made in science education with the development of the National Science Education Standards (NRC, 1996). These standards call for inquiry-based teaching and learning which “refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work.” Students practice inquiry as they “describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations” (NRC, 1996, p. 2).

Researchers have demonstrated that academic achievement is improved by the use of inquiry instruction in K-12 levels (Bransford and Donovan, 2004; Minner et al., 2010). Inquiry instruction has also been examined at the college level and found to be more effective than traditional science instruction for the development of thinking and problem solving (Oliver-Hoyo et al., 2004). University science faculty value inquiry, but identify time, class size, student motivation, and student ability as obstacles to implementing inquiry-based instruction (Brown et al., 2006). A significant result in the theory of inquiry-based learning is Process-Oriented Guided-Inquiry Learning (POGIL, 2016), a student-centered, group-learning instructional strategy and philosophy. POGIL provides a general framework for developing activities implementing guided inquiry in the classroom, and there are now many POGIL inquiry-based learning activities in a wide variety of disciplines. However, while POGIL and other inquiry approaches offer an alternative to lectures-style instruction, they depend on intensive training of instructors to develop and implement inquiry-based activities in their classrooms.

The NSF’s “Improving Undergraduate STEM Education” program (NSF 14-588) provided support for the development of, and experimentation with an intelligent computer system called sInvestigator (science Investigator), that greatly facilitates the development of a wide variety of inquiry-based teaching and learning experiences for learning critical thinking skills. sInvestigator has built-in features to engage the students in understanding, extending, creating, critiquing, and debating evidence-based scientific argumentations in real-life scientific investigations. This involves using science cross-cutting concepts and disciplinary core ideas, giving the students
numerous opportunities to exercise imagination and creativity, and develop critical scientific practices, particularly: (1) Asking questions; (2) Constructing explanations; (3) Engaging in argument from evidence; and (4) Obtaining, evaluating, and communicating explanations (NRC, 2012, p.3). Students’ progress is assessed based on their ability to deal with new problems on their own, still using sInvestigator, but without any help from the instructor.

This report presents a freely available intelligent computer system, called sInvestigator (science Investigator), that helps students develop critical thinking skills in addressing scientific problems, through a rigorous yet easy to employ inquiry-based approach. sInvestigator was developed as a customized version of Cogent (Tecuci et al., 2015; 2018a), which incorporates the latest version of the Disciple learning agent theory and technology (Tecuci, 1988; Tecuci 1998; Boicu et al., 2000; Tecuci et al., 2000; Boicu et al., 2001; Tecuci et al., 2002a; Tecuci et al. 2016a). Disciple agents have been demonstrated in many domains, including critical thinking education in history (Tecuci and Keeling, 1999), course of action critiquing (Tecuci et al., 2001), center of gravity analysis (Tecuci et al., 2002b; Tecuci et al., 2005; Tecuci et al., 2008a), intelligence analysis (Tecuci et al., 2008b; Tecuci et al., 2011; Tecuci et al., 2016b; Tecuci et al., 2018a), intelligence, surveillance and reconnaissance (Tecuci et al., 2019), and cybersecurity (Tecuci et al., 2018b; Huang et al., 2020).

The next section introduces the computational framework of scientific inquiry as discovery of evidence, hypotheses, and arguments, on which sInvestigator is based (Tecuci et al., 2016). Then Section 3 presents a generic inquiry-based teaching and learning experience. Section 4 illustrates the features of sInvestigator with a detailed case study. The rest of the sections present a variety of inquiry-based exercises, many of them based on those described in (Osborne et al., 2004).

Additional materials on critical thinking with sInvestigator, including instructions to download the system for both PC and Mac are available at: http://lac.gmu.edu/sInvestigator/

2. 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.

Students 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 Hk were true, then the sub-hypotheses Hk1 and Hk2 would also need to be true. But if Hk1 were true, then one would need to observe evidence Ek1, and so on. This process leads to the discovery of new evidence by identifying the necessary conditions for hypothesis Hk.
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 hypotheses by considering favoring arguments (under the left, green square) and disfavoring arguments (under the right, pink square), as illustrated in Figure 2.

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

**Figure 2.** Hypothesis in search of evidence.

**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.

3. 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. 
   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.

4. Sample Inquiry with SInvestigator in a Science Class

A classical textbook example of using inquiry in a classroom is presented in (NRC, 2000, pp.5-11). The following is an adaptation of that 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 the Spring break. 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
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.

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 slInvestigator analysis whiteboard in order to reduce space usage and facilitate the visualization of larger argumentations.

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 slInvestigator 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 slInvestigator, as shown in the bottom-right of 6.

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.

![Figure 5. Hypotheses in search of evidence](image)
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 slnvestigator 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, slnvestigator computed the credibility as C (Certain 100%) 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, slnvestigator 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 slnvestigator computed the credibility as C (Certain 100%). The relevance was also assessed as C (Certain 100%), leading slnvestigator to assess its inferential force as C (Certain 100%). Additionally, slnvestigator 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 the investigator 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%), the investigator 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 investigator 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.

Finally, investigator 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. » (adapted from NRC, 2000, pp.5-11).

The next sections present various types of inquiry-based exercises.

5. Analysis of Competing Scientific Theories

5.1. Competing Theories of Light

The aim of this exercise, adapted from (Osborne et al., 2004, pp.31-33), is to explore alternative theories for why we see things, by developing evidence-based argumentations.

5.1.1. Inquiry: How do we see things?

Consider the following competing theories on how we see things:

**Theory 1:** Light rays travel from our eyes onto the objects and enable us to see them.

**Theory 2:** Light rays are produced by a source of light and reflect off objects into our eyes so we can see them.

The students will have to search for evidence on the Internet to determine which one is true. To facilitate their task, they are provided with the following statements that may be used to develop favoring and disfavoring arguments for the two hypothesized theories:

- Light travels in straight lines.
- We can still see at night when there is no sun.
- Sunglasses are worn to protect our eyes.
- If there is no light we cannot see anything.
5.1.2. Argumentations

Inquiry: How we see things?

Theory 1: Light rays travel from our eyes onto the objects and enable us to see them.

Light travels to our eyes not from our eyes

If there is no light we cannot see anything

Theory 2: Light rays are produced by a source of light and reflect off objects into our eyes so we can see them.

Light travels to our eyes from the sun

Sunglasses are worn to protect our eyes

E1 Without light we cannot see anything

E2 Sunglasses protects our eyes

Evidence

E1 Without light we cannot see anything
(During the evening when the Earth has rotated to a position where the light from the sun can no longer reach our part of the Earth (due to its inability to bend around the spherical shape of the Earth), objects on Earth appear black (or at least so dark that we could say they are nearly black). In the absence of a porch light or a street light, the neighbor’s house can no longer be seen; the grass is no longer green, but rather black; the leaves on the trees are dark; and were it not for the headlights of the car, it would not be seen approaching the intersection. Without luminous objects generating light that propagates through space to illuminate non-luminous objects, those non-luminous objects cannot be seen. Without light, there would be no sight.)

E2 Sunglasses protects our eyes
(Sunglasses or sun glasses (informally called shades or sunnies; more names below) are a form of protective eyewear designed primarily to prevent bright sunlight and high-energy visible light from damaging or discomforting the eyes. They can sometimes also function as a visual aid, as variously termed spectacles or glasses exist, featuring lenses that are colored, polarized or darkened.)
Theory 1: Light rays travel from our eyes onto the objects and enable us to see them.

Theory 2: Light rays are produced by a source of light and reflect off objects into our eyes so we can see them.

Light rays travel in straight lines from a source of light (not necessarily the sun)

Light reflects off objects into our eyes so we can see them

If there is no light we cannot see anything

Light travels in straight lines

Light travels to our eyes from the sun

We can still see at night when there is no sun

E1. Without light we cannot see anything

E2. Sunglasses protects our eyes

E3. Light travels in straight line

Sunglasses are worn to protect our eyes

E4. Light production
5.2. Competing Theories of Ice Melting and Water Boiling

In this exercise, adapted from (Osborne et al., 2004, pp.59-62), the students are presented with the contrasting graphs from Figure 8 of temperature against time as ice is heated to water vapor.

![Figure 8. Contrasting graphs of temperature against time as ice is heated to water vapor, reproduced from (Osborne et al., 2004, p. 61).](image)

They have to determine which graph is correct (if any) by developing evidence-based argumentations. Their task is facilitated by presenting them with statements that may support one graph or the other.

5.2.1. Inquiry: How does the temperature vary as a function of time when heating ice to steam?

Potentially useful statements:

- Ice will melt when it is heated and turns into water.
- In solids there are bonds between the particles that hold them together in fixed shape.
- When you heat a substance the supply of heat energy is usually constant.
- Energy is needed to break bonds between particles.
- Ice melts at 0 degrees Celsius and boils at 100 degrees Celsius.
- Whilst energy is being used to break bonds between particles there will be no temperature increase.
- When a substance is heated the particles in it absorb heat energy and move about more quickly, and its temperature increases.
5.2.2. Argumentations

Inquiry: How does the temperature vary as a function of time when heating ice to steam?

- The temperature varies linearly as a function of time when heating ice to steam.

- The temperature increases linearly with heating, as a function of time, except for the intervals corresponding to ice melting and water boiling, when it is constant.

When a substance is heated, its particles absorb heat energy and move more quickly, and its temperature increases.

- The temperature remains constant at 0 degrees Celsius with heating, while the ice is melting.

- The temperature remains constant at 100 degrees Celsius with heating, while the water is boiling.

E1 Temperature of the ice increases linearly with heating
E2 Temperature of liquid water increases linearly with heating
E3 Bonding in solids
E4 Kinetic energy to break bonds between particles
E5 Temperature constant while ice melting
E6 Ice melts at 0 degrees Celsius

Evidence:

E1 Temperature of the ice increases linearly with heating (Initially, the system is solid water at temperature of -20 Celsius. As the heat flows in, the temperature of the ice increases. The slope of this line is the heat capacity of solid water; the slope of the curve is actually 1/mC)

E2 Temperature of liquid water increases linearly with heating (Once all of the solid has been converted to liquid the temperature increases with heat flow. The slope of this line is again related to the heat capacity. However, this time it is the heat capacity of the liquid)

E3 Bonding in solids (In a solid, the attractive forces keep the particles together tightly enough so that the particles do not move past each other. Their vibration is related to their kinetic energy. In the solid the particles vibrate in place.)

E4 Kinetic energy to break bonds between particles (Kinetic energy, the energy of matter in motion, fuels the collisions of atoms, ions, and molecules that are necessary if their old bonds are to break and new ones to form. All molecules store potential energy, which is released when their bonds are broken.)

E5 Temperature constant while ice melting (Next the solid melts. During this time the temperature is constant at 0. Heat flows into the system, but the temperature does not change. At the start of this transition all of the water is solid. As heat flows into the system, the solid begins to melt into a liquid but the temperature stays constant. That is because the energy that is flowing into the system as heat is going into the potential energy of overcoming the intermolecular forces holding the water in a solid lattice.)

E6 Ice melts at 0 degrees Celsius (At temperatures above 0 degrees, pure water ice melts and changes state from a solid to a liquid, water.)
5.3. Competing Theories of Snowman Melting

The aim of this exercise, adapted from (Osbome et al., 2004, pp.50-55), is to determine which snowman - one wearing a coat or the other one not wearing a coat - will melt first, by building evidence-based argumentations.

5.3.1. Inquiry: Which snowman will melt first?

Which snowman will melt first, Fred (the snowman with the coat) or Birt (the showman without the coat)?

5.3.2. Argumentations

![Image of a tree diagram explaining the melting of snowmen with and without coats, based on temperature conditions.]

- **Inquiry:** Which snowman will melt first, Fred (the snowman with the coat) or Birt (the showman without the coat)?

- **Assuming the air temperature is above freezing:** Birt (the snowman without the coat) will melt first.

- **Assuming the temperature is below freezing:** Neither snowman will melt.

- **Birt will melt first because the sun energy will be slowed by the coat from getting to Fred.**
The sun's rays have both heat and light energy in them.

Heat is conducted by molecules vibrating and passing on the heat energy to the next molecule.

The coat will limit the flow of heat energy from the air to Fred, slowing the rate at which its temperature will rise above freezing.

Energy from sun rays flows to snowmen.

Fred's coat is an insulator.

Insulators limit the flow of heat transfer.

Air temperature is above freezing.

Fred's coat is made of an insulating material such as woolen.

E1 Sun radiation
E2 Heat is conducted by molecules vibrating
E3 Insulators slow down heat transfer
6. Predicting, Observing and Explaining the Result of an Experiment

This is an example, adapted from (Osborne et al., 2004, pp.7-11), of a “predict, observe, and explain” experiment to learn about combustion: A burning candle inside a container with water is covered with a glass (see Figure 9). Students are asked to predict what will happen with the candle and the water level inside the glass, perform the experiment, and observe the actual results. Finally they are asked to develop two evidence-based argumentations that explain the results of the experiment.

6.1. Inquiry: Why does the candle burn out?

The students are asked to explain why the candle burns out when it is covered with the glass.

6.2. Argumentation: Candle burns out
6.3. Inquiry: Why does the water level inside the glass raise?
The students are asked to explain why the water level inside the glass raises.

6.4. Argumentation: Water level rises
7. Explaining the Result of a Chemical Experiment

This is an actual experiment conducted in the course taught by prof. Robin Taylor at the Thomas Jefferson High School for Science and Technology, in Fairfax, Virginia.

7.1. Inquiry: Do the experiments confirm the law of conservation of mass?

The aim of this exercise, created primarily by Anya Parekh, is to develop an evidence-based argumentation that explains the results obtained by individual students in a Chemistry experiment designed to verify the Law of Conservation of Mass.

7.2. Argumentation
8. Explaining a Physical Phenomenon

8.1. Dropping a Box

The aim of this exercise, adapted from (Osborne et al., 2004, pp.47-49), is to explore forces that act upon a dropping box and to develop evidence-based argumentations on how an object falls.

8.1.1. Inquiry: How does a box fall?

A box is dropped from an airplane and falls to the ground. The sequence of statements in the boxes below explain how the box falls.

For each box that contains a single statement develop an evidence-based argumentation to show that the statement is true.

For each box that contains multiple statements, develop an evidence-based argumentation to determine which statement is true.

Then compose an argumentation to answer the question: How does a box fall?

1 There is a force of gravity on the box.

2 This acts downwards.

How does the force change throughout the fall?

3a It is roughly the same size throughout the fall.
3b It gets a lot bigger as the box gets closer to the Earth.
3c It is biggest when the box is high up and gets a lot smaller as it falls.

What is the effect of the force on the box?

4a This force makes the box begin to accelerate downwards.
4b This force makes the box begin to move downwards at a steady speed.

5 Once the box begins to move, there is also an air resistance force on it.

In what direction does the air resistance force act?
6a This acts downwards, in the direction the box is going.
6b This acts upwards, in the opposite direction to the box’s motion.

Does the air resistance force change?

7a The size of the air resistance force on the box is constant throughout the fall.
7b The air resistance force gets bigger as the box gets faster.

Should the air resistance force be taken into account?

8a The air resistance force on the box is much smaller than the force of gravity, and so it can be ignored.
8b The air resistance force on the box becomes quite large, and has to be taken into account.

What is the total force on the box?

9a The total force on the box is equal to the force of gravity, and is constant.
9b The total force on the box is the sum of the gravity force and air resistance, and this gets gradually less as it falls, because the air resistance increases.

What is the acceleration throughout the fall?

10a The box has a uniform acceleration throughout its fall.
10b The acceleration of the box is biggest to begin with, and gets gradually less.
   Once the air resistance force becomes equal to the gravity force, the acceleration is zero and the box then falls at a steady speed.
10c The box falls at a steady speed throughout its fall.
8.1.2. Argumentations

Inquiry: Is there a force of gravity on the box?

1: There is a force of gravity on the box

Evidence

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 Gravity</td>
<td>(Gravity is a force that pulls objects down toward the ground.)</td>
</tr>
<tr>
<td>E2 Earth gravity</td>
<td>(Gravity (from Latin gravitas, meaning 'weight'), or gravitation, is a natural phenomenon by which all things with mass or energy including planets, stars, galaxies, and even light brought toward (or gravitate toward) one another. On Earth, gravity gives weight to physical objects)</td>
</tr>
<tr>
<td>E3 Weight direction</td>
<td>(The weight of an object on Earth's surface is the downwards force on that object, given by Newton's second law of motion)</td>
</tr>
<tr>
<td>E4 Gravitational acceleration</td>
<td>(Scientists have combined the universal gravitational constant, the mass of the Earth, and the square of the radius of the Earth to form the gravitational acceleration, ( g_E ). On the surface of the Earth, its value is 9.8 meters per square second or 32.2 feet per square second.)</td>
</tr>
<tr>
<td>E5 Downward acceleration</td>
<td>(In fact, its velocity increases by 9.8 m/s², so by 1 second after an object starts falling, its velocity is 9.8 m/s.)</td>
</tr>
</tbody>
</table>

Inquiry: In what direction does this force act?

2: This acts downwards.

E3 Weight direction
Inquiry: How does the force change throughout the fall?

3a: It is roughly the same size throughout the fall.
C

3b: It gets a lot bigger as the box gets closer to the Earth.
LS

3c: It is biggest when the box is high up and gets a lot smaller as it falls.
LS

Inquiry: What is the effect of the force on the box?

E4 Gravitational acceleration

E4 Gravitational acceleration

E4 Gravitational acceleration

E3 Weight direction (The weight of an object on Earth's surface is the downwards force on that object, given by Newton's second law of motion)

E4 Gravitational acceleration (Scientists have combined the universal gravitational constant, the mass of the Earth, and the square of the radius of the Earth to form the gravitational acceleration, \( g \).
On the surface of the Earth, it's value is 9.8 meters per square second or 32.2 feet per square second.)

E5 Downward acceleration (In fact, its velocity increases by 9.8...

4a: This force makes the box begin to accelerate downwards.
C

4b: This force makes the box begin to move downwards at a steady speed.
LS

5: Once the box begins to move, there is also an air resistance force on it.
C

E5 Downward acceleration

E5 Downward acceleration

E6 Air resistance

E5 Downward acceleration (In fact, its velocity increases by 9.8 m/s², so by 1 second after an object starts falling, its velocity is 9.8 m/s. By 2 seconds after it starts falling, its velocity is 19.6 m/s (9.8 m/s + 9.8 m/s), and so on.)

E6 Air resistance (By definition, air resistance describes the forces that are in opposition to the relative motion of an object as it passes through the air.)

E7 Air resistance direction (By definition, air resistance describes the forces that are in opposition to the relative motion of an object as it passes through...
**E7 Air resistance direction** (By definition, air resistance describes the forces that are in opposition to the relative motion of an object as it passes through the air. These drag forces act opposite to the oncoming flow velocity, thus slowing the object down. Unlike other resistance forces, drag depends directly on velocity, since it is the component of the net aerodynamic force acting opposite to the direction of the movement.)

6a This acts downwards, in the direction the box is going.

6b This acts upwards, in the opposite direction to the box’s motion.

**E8 Air resistance change** (As an object falls, it picks up speed. The increase in speed leads to an increase in the amount of air resistance. Eventually, the force of air resistance becomes large enough to balances the force of gravity.)

7a The size of the air resistance force on the box is constant throughout the fall.

7b The air resistance force gets bigger as the box gets faster.

**E9 Air resistance magnitude** (As an object falls, it picks up speed. The increase in speed leads to an increase in the amount of air resistance. Eventually, the force of air resistance becomes large enough to balances the force of gravity.)

8a The air resistance force on the box is much smaller than the force of gravity, and so it can be ignored.

8b The air resistance force on the box becomes quite large, and has to be taken into account.
9a So the total force on the box is equal to the force of gravity, and is constant.

9b The total force on the box is the sum of the gravity force and air resistance, and this gets gradually less as it falls, because the air resistance increases.

E10 Total force

10a The box has a uniform acceleration throughout its fall.

10b The acceleration of the box is biggest to begin with, and gets gradually less. Once the air resistance force becomes equal to the gravity force, the acceleration is zero and the box then falls at a steady speed.

10c The box falls at a steady speed throughout its fall.

E11 Variation of acceleration

E11 Variation of acceleration

E11 Variation of acceleration

gravity. At this instant in time, the net force is 0 Newton; the object will stop accelerating.
8.2. Playing Golf

This exercise, adapted from (Osborne et al., 2004, pp.56-58), considers the situation where a golfer has driven a golf ball and the ball is falling freely onto the green. The students are asked to develop evidence-based argumentations in order to determine the truthfulness of a number of statements. The students will need to have some knowledge of the concepts of force, velocity, distance, weight, air resistance and speed.

8.2.1. Inquiry

Which of the following statements are true and which are false?

- The only forces on the ball, once it's been hit by the club, are its weight and air resistance.
- The force from the golf club acts on the ball until it stops moving.
- The force which he or she has put into the ball by striking it is being used up as it travels through the air.
- The force from his or her drive wore off at the point where the ball started to drop.
- The net force is always in the same direction as the ball is moving.
- The various forces on the ball can't be thought of as one single net force.
8.2.2. Argumentations

The only forces are on the ball, once it's been hit by the club, are it's weight and air resistance.

The force from the golf club acts on the ball until it stops moving.

The force exerted by the bat on the ball exists only during their interaction, which is the moment of impact.

Gravity exists wherever there is mass.

Air resistance always exists.

E1 Force is interaction (In physics, a force is any interaction that, when unopposed, will change the motion of an object.)

E2 Interaction and force (A force is a push or pull upon an object resulting from the object's interaction with another object. Whenever there is an interaction between two objects, there is a force upon each of the objects. When the interaction ceases, the two objects no longer experience the force.)

E3 Gravity exists wherever there is mass (Gravity is a force between two masses, so gravity exists wherever there is mass.)

E4 Air resistance always exists (With only the gravitational force, the object has a constant acceleration and the motion is fairly simple to model. However, objects on the surface of the Earth usually have an air resistance force on them also.)

E5 Direction of net force (The direction of the net force (or unbalanced force) acting upon an object is the same as the direction of the acceleration. ... While the net force may not be in the same direction which the object is moving, it is always in the direction that the object is accelerating.)
The force from the golf club acts on the ball until it stops moving.

The force exerted by the bat on the ball exists only during their interaction, which is the moment of impact.

The force which he or she has put into the ball by striking it is being used up as it travels through the air.

The force exerted by the bat on the ball exists only during their interaction, which is the moment of impact. It results in an initial speed which is changed due to the gravity and air resistance acting on the ball.
The force from his or her drive wore off at the point where the ball started to drop.

The force exerted by the bat on the ball exists only during their interaction, which is the moment of impact. It results in an initial speed which continuously decreases until it becomes zero and then changes direction due to the gravity and air resistance acting on the ball.

E1 Force is interaction    E2 Interaction and force

The net force is always in the same direction as the ball is moving.

The direction of the net force is the same as the direction of the acceleration which, in this case is not the same as the ball is moving.

E3 Direction of net force

E4 Air resistance always exists (With only the gravitational force, the object has a constant acceleration and the motion is fairly simple to model. However, objects on the surface of the Earth usually have an air resistance force on them also.)

E5 Direction of net force (The direction of the net force (or unbalanced force) acting upon an object is the same as the direction of the acceleration. ... While the net force may not be in the same direction which the object is moving, it is always in the direction that the object is accelerating.)

E6 Net force is the vector sum of forces (Net force is the vector sum of forces acting on a...
9. Classifying an Organism

The aim of this exercise, adapted from (Osborne et al., 2004, pp.26-30), is to determine whether the single cell organism euglena is a plant, an animal, or another type of organism, by developing an evidence-based argumentation.

9.1. Inquiry: What type of organism is Euglena?

Euglena is an organism that has both plant and animal characteristics, including the following ones:

- Euglena has two outer layers.
- Euglena contains chloroplasts.
- Euglena has a nucleus.
- Euglena is a single cell.
- Euglena can absorb food from its surrounding.
- Euglena confused early scientists.
- Euglena is normally green.
- The nucleus contains DNA and controls the cell activities.
- Chloroplasts enable a cell to photosynthesize.
- A vacuole controls the amount of liquid in a cell.
- Euglena swims through water.
- Euglena can make its own food.
Develop argumentations to determine which of the following hypothesis is true:

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

9.2. Argumentations
Inquiry: What type of organism is Euglena?

- LS Euglena is a plant
- LS Euglena is an animal
- C Euglena is another type of organism, neither plant nor animal
- C Euglena has animal features
- C Euglena has plant features
- C Euglena feeds on organic matter
- C Euglena is able to move
- C Euglena has specialized sense organs
- C Euglena is able to respond rapidly to stimuli

Evidence

E1 Euglena photosynthesis (Euglenas create their own food through photosynthesis, the process of absorbing sunlight to synthesize foods from carbon dioxide and water.)

E2 Euglena feeds by autotrophy (Euglenas contain chloroplasts. Most species of Euglena have photosynthesizing chloroplasts within the body of the cell, which enable them to feed by autotrophy, like plants.)

E3 Euglena feeds on organic matter (When feeding as a heterotroph, Euglena takes in nutrients by osmotrophy, and can survive without light on a diet of organic matter, such as beef extract, peptone, acetate, ethanol or carbohydrates.)

E4 Euglena swims through water (Euglena swims through water Euglena move by a flagellum, which is a long whip-like structure that acts like a little motor.)

E5 Euglena is light sensitive (Euglena is light sensitive. It has an organelle called stigma - a light-sensitive spot that allows the Euglena to detect light, so that it may move towards it in order to conduct photosynthesis.)

E6 Euglena is a single cell (Euglena is a single cell. Euglena are single-celled organisms that belong to the genus Protist. As such, they are not plants, animal or fungi. In particular, they share some characteristics of both plants and animals.)
10. Arguing about a Socio-Scientific Issue

The aim of this exercise, adapted from (Osbome et al., 2004, pp.37-39), is to provide an opportunity for students to engage in argumentation about a socio-scientific issue - the funding of a new zoo - and to provide justifications for their point of view by doing internet research to construct arguments, justified with evidence, either for or against the new zoo.

10.1. Inquiry: Should we have a new zoo?

To facilitate students’ Internet research and the development of their argumentation, they are asked to consider the following sets of questions.

Questions to stimulate agreement with zoos:

- Are wild animals killed by hunters and poachers?
- Are animals in zoos well fed?
- Are animals in zoos safe from predators that want to kill them?
- Do zoos allow you to see a large number of different animals?
- Would animals have become extinct if it wasn't for zoos?
- Can you see wild animals on the television living in their natural homes?
- Do wild animals have to find their own food?
- Can zoos release animals back to the wild?
- Do zoos allow scientists to study rare animals?

Questions to stimulate disagreement with zoos

- Do animals in the wild have lots of places to live in?
- Is it cruel to keep animals in cages?
- Can wild animals be protected in parks and nature reserves?
- Are wild animals afraid of human beings?
- Can animals be bored and lonely in zoos?
- Can animals breed in zoos?
10.2. Argumentation
11. Exploring a Mystery

Amelia Mary Earhart (born July 24, 1897 – disappeared July 2, 1937, declared dead January 5, 1939) was an American aviation pioneer and author. During an attempt to make a circumnavigational flight of the globe in 1937 in a Lockheed Model 10-E Electra, Earhart and navigator Fred Noonan disappeared over the central Pacific Ocean near Howland Island (https://en.wikipedia.org/wiki/Amelia_Earhart).

11.1. Inquiry: What happened to Amelia Earhart?

The aim of this exercise is to explore various theories on Amelia Earhart’s disappearance by developing evidence-based argumentations.

Four possible theories are to be explored:

- Amelia Earhart’s Electra landed on the Nikumaroro Island and died of thirst or starvation.
- Amelia Earhart purposely disappeared and assumed a new identity.
- Amelia Earhart was captured by Japan and executed as a United States spy.
- Amelia Earhart’s Electra crashed into the ocean and sank.
11.2. Argumentations

Topic: Amelia Earhart Mystery

Inquiry: What happened to Amelia Earhart?

- L: Amelia Earhart’s Electra landed on the Nikumaroro Island and died of thirst or starvation.
- LS: Amelia Earhart purposely disappeared and assumed a new identity.
- LS: Amelia Earhart was captured by Japan and executed as a United States spy.
- L: Amelia Earhart’s Electra crash into the ocean and sank.
49
Evidence


E8 Unsuccessful search of Nikumaroro
(A week after the disappearance, naval aircraft from the Colorado flew over several islands in the group including Gardner Island (now called Nikumaroro), which had been uninhabited for over 40 years. The subsequent report on Gardner read: "Here signs of recent habitation were clearly visible but repeated circling and zooming failed to elicit any answering wave from possible inhabitants and it was finally taken for granted that none were there..." [N 25] [N 25] Memo from Senior Aviator, USS Colorado, to The Chief of the Bureau of Aeronautics, "Aircraft Search of Earhart Plane." Their commander Capt Friedell made no note of "recent habitation" in his official summary. [Finding Amelia DVD, Annapolis, Maryland: Naval Institute Press, 2006. DVD: Contents: Reports: Lambrecht.pdf, p. 3])

E9 Transmissions attributed to Nikumaroro Island were false
(David Jourdan, a former Navy submariner and ocean engineer specializing in deep-sea recoveries, has claimed any transmissions attributed to Gardner Island were false. Through his company Nauticos he extensively searched a 1,200-square-mile (3,100 km2) quadrant north and west of Howland Island during two deep-sea sonar expeditions (2002 and 2006, total cost $4.5 million) and found nothing. The search locations were derived from the line of position (157–337) broadcast by Earhart on July 2, 1937. [105])
E19 wrecked aircraft resembling Electra (While Angwin died in 2001, David Billings, an Australian aircraft engineer, has continued to investigate his theory. Billings claims that the serial numbers written on the map, "6000F-P-32H C/N 1055", represent: • a 600 hp (450 kW) Pratt & Whitney R-1340-63H1 model engine and; • "Constructor's Number 1055", an airframe identifier. These would be consistent with a Lockheed Electra 10E, such as that flown by Earhart, although they do not contain enough information to identify the wreck in question as NR.16020. [Billings, David, 2000] Billings, David. "AirCraft Search Project in Papua New Guinea." Wings Over Kansas. 2000. Retrieved: March 27, 2012. http://www.wingsoverkansas.com/earhart/air50u/)

E20 Earhart and Noonan captured and executed (In 1966, CBS and NBC's 60 Minutes ran a story asserting that Earhart and Noonan were captured by the Japanese, after which they were killed by a firing squad. The story was based on a book written by C. H. Gordon, who claimed to have talked to a former Japanese intelligence officer who had worked with the pilots. The book, "The Last Journey of Amelia Earhart" by C. H. Gordon, was published in 1980. While there is no concrete evidence to support the story, it has been widely reported and discussed."


E22 Japanese not involved in Earhart disappearance (Jackie Cochran, another pioneering aviator and one of Earhart’s friends, made a postwar search of numerous files in Japan and was convinced the Japanese were not involved in Earhart’s disappearance.) [Cochran 1954, p. 160] Cochran, Jacqueline. Stars at Noon. Boston: Little, Brown and Company, 1954.)
Inquiry: What happened to Amelia Earhart?

- Amelia Earhart's Electra landed on the Nikumaroro island and died of thirst or starvation.
- Amelia Earhart purposely disappeared and assumed a new identity.
- Amelia Earhart was captured by Japan and executed as a United States spy.
- Amelia Earhart's Electra crash into the ocean and sank.

- Amelia Earhart's Electra had a fatal problem.
- Amelia Earhart's Electra sank into the ocean.
- Amelia Earhart's Electra had an engine malfunction.
- Amelia Earhart's Electra ran out of fuel.
Amelia Earhart's Electra had an engine malfunction.

Amelia Earhart's Electra ran out of fuel.

Amelia Earhart's Electra ran into the ocean.

E25 Howland Island very small
(Their intended destination was Howland Island, a flat, sparsely populated island located 2,900 miles (4,640 km) south of Hawaii. It was a major navigation aid for airplanes flying to the South Pacific Islands.

E26 Indistinguishable signals
(The radios used by the crew were not powerful enough to generate a strong signal. The radio signals were not strong enough to be heard.

E27 Electra was not fully fueled
(Earhart and Noonan had planned to fly from Howland Island to the Marshall Islands, but they were not fully fueled. The Electra was not fully fueled. Earhart and Noonan had planned to fly from Howland Island to the Marshall Islands, but they were not fully fueled. The Electra was not fully fueled.

E28 Earhart expertise issues
(There were some issues with the Electra's navigation system. The Earhart's expertise in the direction-finding system was questioned.

E29 Earhart expertise issues
(Some sources have noted Earhart's apparent lack of understanding of her direction-finding system, which had recently been fitted to the aircraft.

E30 Direction miscalculation
(William L. Phippen, the navigator on Earhart and Noonan's original flight path, studied navigational tables for July 2, 1937 and thought Noonan may have miscalculated the "single line approach" intended to "hit" Howland Island.

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E29 Earhart expensive 

Some sources have noted Earhart’s apparent lack of understanding of her direction-finding system, which had recently fitted to the aircraft just prior to the flight. The system was equipped with a new receiver from Bendix that operated on five wavelengths (bands), marked 1 to 5. The long antenna was equipped with a tunable receiving coil that changed the effective length of the antenna to allow it to work efficiently at different wavelengths. The tuner on the antenna was also marked with five settings, 1 to 5, but, critically, these were not the five same frequency bands as the corresponding bands on the radio. The two were close enough for settings 1, 2, and 3, but the higher-frequency settings, 4 and 5, were entirely different. Earhart’s only training on the system was a brief introduction by the Guer at the Lockheed factory, and the setup had not come up. A card displaying the bands settings of the antenna was mounted so it was not visible. Some historians noted that higher-frequency bands would allow better accuracy and longer range [Elgin and Marka Long, “Amelia Earhart: The Mystery Solved”, p.136; Long, Edgar M. and Marka K. Amelia Earhart: The Mystery Solved. New York: Simon & Schuster, 1999. ISBN 0-684-82908-6.]

E30 Directional inaccuracies (William J. Hillhouse, the navigator on Anna Elizabeth Beech’s flight which followed Earhart and Noonan’s original flight path, noted navigational failures for July 7-8, 1937 and thought Noonan may have miscalculated the “single-line approach” intended by the Howard-Henderson Model 606, 1995, pp. 58-60) 


E31 Earhart unable to determine direction of Morse signals (Her 728 transmission said she couldn’t hear the beacon and asked them to send voice signals so she could try to take a radio bearing. … They couldn’t send voice at the frequency she asked for, so Morse code signals were sent instead. Earhart acknowledged receiving Morse but said she was unable to determine their direction. [Jacobson, Randall S., 2009; Jacobson, Randall S., PhD. “The Final Flight, Part 3: At Honolulu (HNL)” Togar.org. Retrieved July 10, 2019. http://宜宾.com/images/short/Antenna/Research/Research/Research/ShortFlight%21FinalFlight%21FirstNet.htm]

E32 Noonan expert navigator (Through contacts in the Los Angeles aviation community, Fred Noonan was subsequently chosen as a second navigator because he had significant additional factors which had to be dealt with while using celestial navigation for accurate timekeeping. [Jacobson, 2009, p. 60; and Garrett, 2015, p. 45-50]. He had vast experience in both marine (he was a licensed third-class captain) and flight navigation. Noonan had recently left Pan Am, where he established most of the company’s (Chris Cooper) overseas routes across the Pacific. Noonan had also been responsible for training Pan American’s navigators for the route between San Francisco and Manila. [Gosch, 1926, p. 175, 189]. Noonan also navigated the China Clipper on its first flight to Manila, according to Almany under the command of Captain Ed Noon, on November 22, 1933.) The original plan was for Noonan to navigate from Hawaii to Honolulu, but, a particularly difficult portion of the flight. Then Noonan would continue with Earhart to Australia and she would proceed on her own for the remainder of the project. [Long, Edgar M. and Marka K. Amelia Earhart: The Mystery Solved. New York: Simon & Schuster, 1999. ISBN 0-684-82908-6. Petrie, David I., and Harold Gutt, “Chasing the Back,” Around the World in Eighty Days. New York: Rand McNally & Company, 1921. Groce, William Steadman. Skyway to Asia. New York: Longmans, Green, 1916. No CARR.

E33 Communication problems (Another cited cause of possible confusion was that the Maris and Earhart planned their communication schedule using five systems set a half hour apart, with Earhart using Greenwich Civil Time (UTC) and the Maris using a New Zealand time service, which would have been 12 hours behind the United States West coast. [Elgin and Marka Long, “Amelia Earhart: The Mystery Solved”, p. 136].]
Amelia Earhart's Electra had a fatal problem.

Amelia Earhart's Electra ran out of fuel.

Amelia Earhart had no place to land.

Electra was not fueled enough for the planned flight.

Electra lost its direction and ran out of fuel.

Electra was not fueled enough for the planned flight.

Electra ran out of fuel.

The pilots made mistakes in navigating Earhart toward destination.

Electra was not able to properly communicate with the destinations.

Electra had low accuracy. Electra did not function properly.

Electra had low accuracy. Electra did not function properly.

Electra gas running low.
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Several exercises on the sInvestigator website and in this report are adaptations of those defined by Jonathan Osborne, Sibel Erduran and Shirley Simon (2004). Xiaohan Ding contributed to them.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

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