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Defining and Developing "Critical Thinking" Through Devising and Testing Multiple Explanations of the Same Phenomenon

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Most physics teachers would agree that one of the main reasons for her/his students to take physics is to learn to think critically. However, for years we have been assessing our students mostly on the knowledge of physics content (conceptually and quantitatively). Only recently have science educators started moving systematically towards achieving and assessing this critical thinking goal. In this paper we seek to show how guiding students to devise and test multiple explanations of observed phenomena can be used to improve their critical thinking.

The Next Generation Science Standards[1] consider science practices (activities that resemble the work of scientists) to be one of the three foci of science education. In the standards we see the pairings of specific content ideas with "best fitting" science practices. For example, according to high school Performance Expectation for the Forces and Interactions, the students should be able to demonstrate that they can

> **"plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current." (High School, Physical Science, concept 2 standard 5.)**

In other words students need to know how to design an experiment to produce desired evidence. This is not a traditionally assessed aspect of learning physics. The science practices required in the NGSS are

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Similar practices are outlined in revised Advance Placement 1 and 2 physics courses.[2] These lists make the fuzzy "critical thinking" goal much more concrete and specific; however, such goals are new for many teachers. This paper will help you design activities that engage students in many of those practices, specifically in noticing, coming up with multiple explanations/models of the observed phenomena, experimentally testing them, and evaluating assumptions that are crucial when students are developing their own explanations. Multiple examples of such processes can be found in the history of science.[3] Our students might be familiar with them from the differential diagnosis by Dr. House in the television show "House" or the process of solving crimes employed in the show "CSI".

Teaching students to notice, devise multiple explanations, and test them

To help students learn to notice important features of a physical phenomenon, devise multiple explanations for those features, and test them, we need to repeatedly engage them in the activities that require using these practices. Devising multiple explanations is a very challenging task for a teacher who knows the "correct" explanation. However, if you let students observe a simple phenomenon (without asking them first to predict its outcome) and then ask them to come up with as many explanations as possible without using scientific terms, you will see how many explanations students devise. As the students are not put on the spot making predictions and are only asked to say what they see, this step removes their original fear of telling the "wrong" answer and helps them become brave enough to engage in a real scientific discussion. Do not judge students' responses at this time, but make a list of their proposed explanations on the board and invite them to come up with ways to experimentally test those (avoid the word "prove").

Do not discuss with the students how reasonable these explanations are, but accept them all as provisionally correct for the time being and then ask the students to design experiments to test every one of those explanations. Testing implies designing an experiment, predicting its outcome using the explanation under test, running the experiment, and comparing the outcome to the prediction. Such a process allows the students to eliminate different explanations and to be left with those (usually one) that cannot be eliminated. Note the

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difference between the explanation and the prediction: An explanation is a synonym for a hypothesis. An explanation answers the question of how or why something happened. There can be many explanations for the same phenomenon. An explanation should be experimentally testable. A prediction is a statement of what will happen in a particular experiment if the explanation under test is correct. A prediction can *only* be made for a specific experiment. Thus, students should not be asked to make predictions until they have first designed a testing experiment (including thought experiments).

In this paper we will take the reader through several exercises that show how to implement this technique and then we will discuss the "science" aspects and the "art" aspects of the process. Although there is a whole learning approach—Investigative Science Learning Environment (ISLE)[4]—that employs this strategy to help students construct new knowledge, in this paper we show how to develop the above practices by following any curriculum by just engaging your students in solving experimental problems. *The Physics Teacher* readers can learn the essence of ISLE in the paper published in 2014.[5]

In our experience the following five points are important:

1. Students need to observe a simple phenomenon that they can describe in simple words.
2. The students need to work in groups and share what they think with the group first, discuss it, and come to a consensus before sharing the ideas with the whole class. Whiteboarding is very useful here.
3. The students need to notice all relevant aspects of the phenomenon. Noticing is greatly enhanced if the students do not predict the outcome before they watch the phenomenon, but instead are encouraged to say everything they observed and to use simple language (no science terms) when doing it. Making no predictions and using simple terms are crucial for the success of the process.
4. The students need to devise explanations that could explain important features of the phenomenon (here the teacher helps focus on the important features). While devising explanations, the students need to think of multiple explanations that need to be experimentally testable ("little invisible men did it" is not a testable explanation) and to be tolerant of their peers' explanations. These multiple explanations naturally appear as students work in groups.
5. The students need to accept all explanations as "correct" for the time being even if they do not like some of those, and then design experiments whose outcomes they can predict using all of the explanations (testing experiments). Thus, they need to learn to differentiate between the explanations and the predictions of the outcomes of the experiments.

In the process outlined above the role of the teacher is crucial. She/he needs to support and encourage students who might be hesitant to devise explanations and test them at first. The teacher also needs to have equipment readily available for possible testing experiments. Our experience and the experience of many teachers using this method show that in a proper collegiate and friendly atmosphere where all ideas are respected, students very quickly adopt expert physics behaviors, i.e., propose their ideas, test them, and feel comfortable rejecting them experimentally.[6] As far as teachers are concerned, after a few tries one accumulates enough experience to feel comfortable with unexpected explanations that students devise and anticipate what equipment students might need for testing. The key here is to listen to the students and trust that they *can* do it.

Below we show three examples of activities that will engage your students in observing physical phenomena, devising multiple explanations for them, and testing experimentally these explanations.

Problem 1: What does the scale read?[7]

Experiment: Place a plastic container (made from a bottle with the top cut off) with water on a scale and notice the reading [see Fig. 1(a)]. Hang a 1-kg object

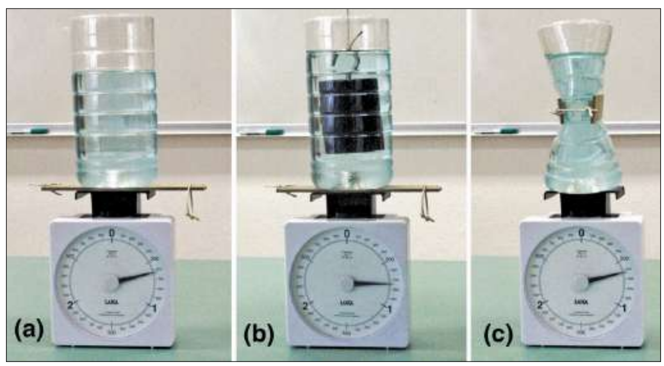

Fig. 1. (a) and (b) Observing what happens when an object hanging on a string is submerged in water inside a container placed on a platform scale. (c) Outcome of testing experiment 1: changing the shape of the container with no object in it so that the height matches the height with the submerged object. The cardboard "squeezers" are on the scale in the first two photos to make the mass the same.

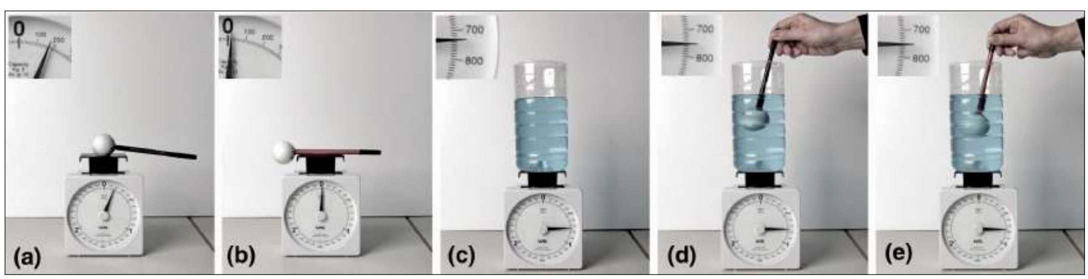

Fig. 2. (a)–(c) Preparing testing experiment 2. Outcome of testing experiment 2: submerging a Ping-Pong ball filled with (d) sand and (e) a regular ball in the container with water.

Table I. (a) Hypotheses explaining the rise of the scale reading and corresponding testing experiments. (b) The logical flow: first students generate multiple hypotheses (I), then they design testing experiments (II) and make predictions based on the hypotheses under test (III), conduct the experiments (IV), compare the outcomes to the predictions (V), and proceed to rejecting some of the hypotheses and to the final judgment (VI).

Testing experiment / Hypothesis explaining the original observation	**Testing exp. 1:** Squeeze the container to achieve the same increase in water level.	**Testing exp. 2:** Submerge each of two Ping-Pong balls, one filled with sand, in the same container (separately).
Hypothesis 1. The higher the level of water the more pressure on the scale.	**Prediction** *Higher water level with the same bottom area should make the scale read more.*	
Hypothesis 2. There is more "stuff" on the scale (mass, or part of it, of the immersed object is somehow added to the mass of the water).	**Prediction** *The scale reading should not change.*	**Prediction** *The sand-filled Ping-Pong ball should make the scale read more than the regular one.*
Hypothesis 3. The water exerts an upward force on the submerged object that depends not on the mass of the submerged object but on its volume, and thus the object exerts an equal in magnitude and downward force on the water, according to Newton's third law. This force makes water press harder on the scale.	**Prediction** *The scale reading should not change.*	**Prediction** *The increase in the scale reading should be the same for both balls.*
(a)	**Outcome of testing exp. 1:** No change in the scale reading.	**Outcome of testing exp. 2:** Same increase in scale reading.

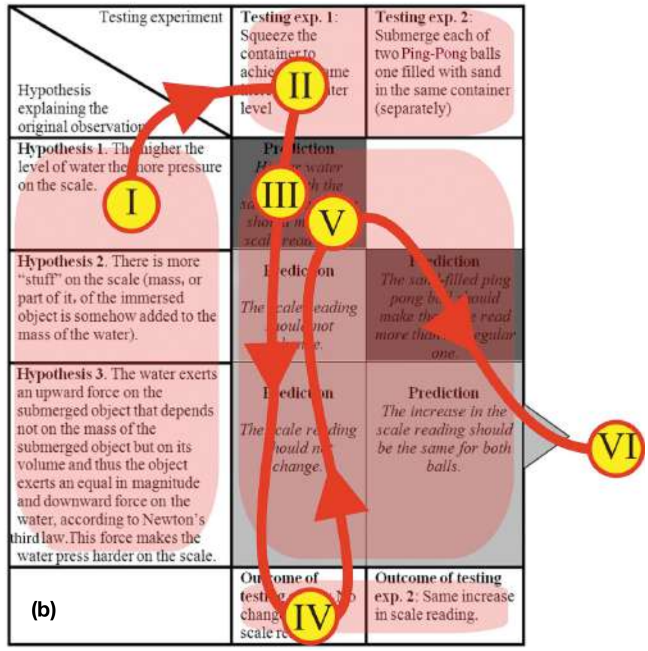

Table II. Legend for a TME chart.

LEGEND	
	Prediction matches the outcome and is helpful.
	Prediction does not match the outcome.
	Prediction matches the outcome, but is not helpful in solving the problem.
	Final accepted hypothesis.

from a string and submerge it in the water so that the bottom of the object does not touch the bottom of the container.

Noticing: The scale reading increases and the water level goes up [Fig. 1(b)].

Usually students easily explain the rise of water by the volume of the submerged object, but they explain the increase in scale reading in many different ways (from now on we will call these different explanations "hypotheses").

Below we show the process of eliminating different hypotheses. As this is not a linear process, we use a Testing Multiple Explanations (TME) chart to help teachers with the logical flow of the process. Table I is an example of such a chart for this particular experiment (to simplify the comprehension of the table, first read the hypotheses in the very left columns and then read the experiments testing each hypothesis in a corresponding row). The hypotheses explaining the original experiments and follow-up testing experiments were suggested by high school students, college students, and pre-service physics teachers. The outcomes of the experiments that are listed in the table are shown in Figs. 1 and 2. The legend for the charts is shown in Table II.

Based on the outcomes of the testing experiments, the students conclude that hypotheses 1 and 2 can be eliminated and hypothesis 3 cannot. Thus, the increase of the reading of the scale might be due to the object pushing on the water.

Students can solve this problem before they learn about buoyant force as a motivator for it, or after. The main idea is that they generate multiple explanations of the observed phenomenon and then design experiments whose outcomes they can predict using those hypotheses. In our experience, this is a great activity for pre-service teachers and physics graduate students alike.

Problem 2: What does a balloon say?

Experiment: Poke an inflated rubber balloon with a needle and listen.

Noticing: Explosion-like loud sound ("bang").

Students need to explain what makes the sound so loud. This example illustrates how, without careful observations, one can overlook important aspects of the original phenomena. In this case students commonly overlook that in addition to the bang, the balloon's rubber does not have a small hole in it, but it is ripped significantly. Because they tend to overlook an important feature of the original experiment, the students often have to go through two cycles to figure out why the balloon makes a loud sound. The TME chart in Table III shows students' hypotheses explaining the bang and the subsequent testing. Figure 3 shows the outcomes of the testing experiments for students' hypotheses and the experiment that improves their skills in observation.

Based on the results in the table we can conclude the following:

> Compressed air is a necessary condition for loud sound but the wall is also important. The wall should quickly go away, leaving a large hole for the air to expand quickly [Fig. 3(e)]. When poking the balloon with a needle, the stretched rubber collapses and creates the hole in short enough time. When using the plastic bag, hitting with a palm caused the bag to rupture in a large hole and allows the air to expand quickly [Fig. 3(g)].

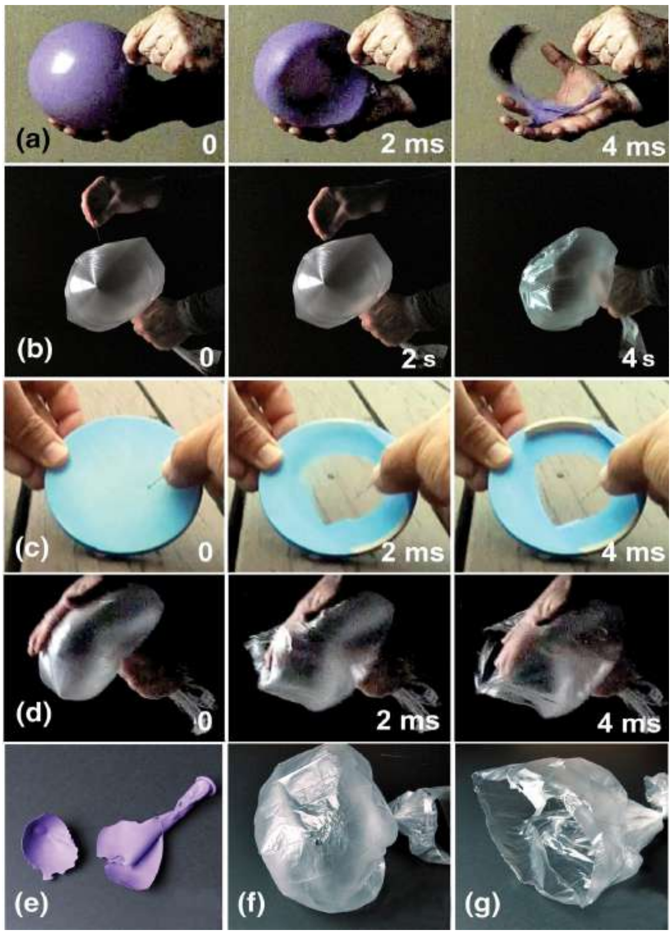

Fig. 3. (a) Poking an air-filled balloon with a needle (original observation); (b) poking an air-filled plastic bag with a needle (testing experiment 1); (c) poking a piece of a balloon rubber stretched on an embroidery hoop (testing experiment 2); (d) exploding an air-filled plastic bag by hitting it with a hand (testing experiment 3); (e) air-filled balloon after poking (new observation); (f) plastic bag after poking with a needle; (g) plastic bag after hitting with a hand. Experiments (a), (c), and (d) have been recorded with a high-speed camera. Times are added only to show a typical duration of each experiment.

Table III. Testing hypotheses explaining the bang produced by a poked balloon.

		1st cycle		2nd cycle
	Testing experiment / Hypothesis explaining the original observation	**Testing exp.1:** Poke inflated plastic bag with a needle.	**Testing exp. 2:** Poke flat stretched piece of rubber (cut from the balloon).	**Testing exp. 3:** Hit the inflated plastic bag with hand.
1st cycle	**Hypothesis 1.** Loud sound is the result of tearing the elastic wall only.	**Prediction** *no loud sound*	**Prediction** *sound should be loud**	
1st cycle	**Hypothesis 2.** Loud sound is the result of expansion of air only.	**Prediction** *sound should be loud*	**Prediction** *no loud sound*	
More observations are needed after both hypotheses are rejected. When we examined the exploded balloon -- it is ripped; the hole is large [see Fig. 3(e)].				
2nd cycle (improved hypothesis)	**Hypothesis 3.** Loud sound is the result of sudden tearing of the wall AND expansion of air. The role of the wall is to break instantly and to let the air out quickly.	**Prediction** *no loud sound*	**Prediction** *no loud sound*	**Prediction** *loud sound*
		Outcome of testing exp. 1: No loud sound; balloon leaks slowly.	**Outcome of testing exp. 2:** no loud sound	**Outcome of testing exp. 3:** Lound sound; large hole in the plastic bag.

* *Some sound can be heard but it is not as loud as the sound in the original experiment.*

Here students do not need any specific knowledge of physics to arrive to the above conclusion. They can work on this problem at the beginning of the school year as an example of how one thinks as a physicist or during any time of the school year when students need a boost in interest and excitement.

Problem 3: What is happening to the balloon?[8]

The following example shows the importance of evaluating assumptions and collecting enough data to propose hypotheses. Unlike the previous two examples, this one requires knowledge of Newton's laws and buoyant force.

> ***Experiment:*** Place several (three) effervescent tablets inside a balloon and add water to it. Tie the balloon and place it on the scale (Fig. 4).
> ***Noticing:*** As the balloon is expanding, we notice a decrease in the reading of the scale. The TME chart in Table IV shows students' hypotheses explaining the decrease of the reading of the scale and subsequent testing.

Table IV indicates that the hypothesis explaining the decrease of the reading of the scale is the upward buoyant force exerted by the air on the balloon. We leave the balloon on the scale and continue measuring. If the above hypothesis is correct, we expect that the balloon will eventually reach the maximum size (when all the tablets are dissolved), and at that point the scale reading will be the smallest. Figure 5 shows what happens to the balloon. The balloon reaches its biggest size in about half an hour and then starts to shrink slowly. Based on the "buoyant force" hypothesis, the scale reading should start to increase when the balloon volume starts to decrease, but the scale reading continues to decrease. It looks like the initial hypothesis 1 that was rejected because we did not observe any bubbles should be revisited. The prediction that we should see bubbles if the balloon is leaking was

Fig. 4. Balloon on the scale. The tablets are inside and the balloon is expanding.

Table IV. Testing hypotheses explaining the decrease of the reading of the scale.

Testing experiment / Hypothesis explaining the original observation	Testing exp.1: Put an object of standard mass on the scale.	Testing exp. 2: Wet the balloon with soap and water.	Testing exp. 3: Repeat the experiment using rigid bottle instead of a balloon.
Hypothesis 1. The balloon is leaking.	**Prediction**	**Prediction** *We should see bubbles.* **(Assumption*)**	
Hypothesis 2. The scale produces faulty readings (it drifts).	**Prediction** *The reading of the scale should change in time.*		
Hypothesis 3. Total mass decreases due to "some reaction" (some students mention conversion of mass to energy, $E=mc^2$).	**Prediction**	**Prediction**	**Prediction** *The reading of the scale should decrease.*
Hypothesis 4. Gas is produced which is "lighter than the air" and it lifts the balloon off the scale.	**Prediction**	**Prediction**	**Prediction** *The reading of the scale should decrease.*
Hypothesis 5. As the balloon is expanding, the buoyant force exerted by the outside air on the balloon is increasing.	**Prediction**	**Prediction**	**Prediction** *As the volume of the bottle does not change, the reading should be the same.*
	Outcome of testing exp. 1: The scale reading remains constant.	**Outcome of testing exp. 2:** No bubbles can be observed.	**Outcome of testing exp. 3:** The scale reading remains constant.

**We assumed leaking is large enough that it will produce visible bubbles.*

based not only on the hypothesis itself but also on the assumption that bubbles are big enough to be seen using soap solution. If we did not assume this, the outcome of the testing experiment 2 would be inconclusive and we would not have rejected this hypothesis.

Now we need to test the leaking of the gas hypothesis in a new experiment that will detect small leaks. Knowing that effervescent tablets release carbon dioxide when added to water, we can put the balloon and the carbon dioxide probe in a container and measure the concentration of carbon dioxide around the balloon [Fig. 5(b)]. If the leaking hypothesis is correct, this concentration should increase. The results of the experiment are shown in Fig. 5(c).

We can conclude that the change of the scale reading is due to the air pushing up on the balloon *and* the slow leaking of the balloon through the skin. The first phenomenon is dominant at the beginning, but later the second one takes over. The second reason would not be found if we did not collect enough data. This example highlights the importance of careful observations to generate correct explanations of phenomena.

Discussion

What aspects of science and art of teaching do the above problems and their analysis highlight? The science of teaching is in knowing how to approach such problems, how to help students be successful, and at the same time experience the spirit of science practice (creativity, uncertainty in the answer, and tolerance of the ideas of others). Specifically, the teacher has to make sure that the students spend time and effort noticing things, that all hypotheses are accepted as equal prior to testing, that students are testing the hypotheses and not their intuition, and that they distinguish between the hypotheses and predictions of the outcomes of the experiments. These steps can be learned using existing curriculum materials,[9] attending workshops,[10] reading papers,[11] etc. The art part comes into play when the teacher needs to be genuinely excited about such problems, to be able to find/create problems that are exciting for students,[12] to be comfortable with students proposing new, unexpected hypotheses, and having strong "faith" in students' ability to design experiments to test these. Being a facilitator and a cheerleader is crucial in this

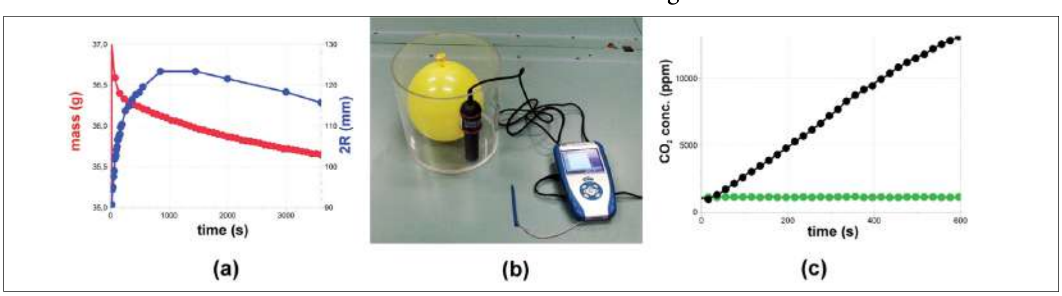

Fig. 5. (a) Time dependence of the scale reading (red) and the average diameter of the balloon (blue) during the one-hour interval. Average diameter of the balloon has been determined from photos. (b) Setup for measuring the carbon dioxide concentration (we used the Vernier CO_2 probe). (c) Time dependence of carbon dioxide concentration around two balloons: black dots – balloon with three effervescent tablets and water, green dots – control experiment, balloon filled with air (using a bike pump).

process as students are not usually accustomed to this way of learning. The most exciting part is when students themselves find suitable problems and the teacher needs to be a part of the solving process, not knowing the final answer. One just has to observe and notice; it seems like the observations (of physical phenomena and of your students) are where science and art meet.

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