Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes (revised 2/12)

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Little attention is given to how the processes of scientific inquiry should be taught. It is apparently assumed that once teacher candidates graduate from institutions of higher learning they understand how to conduct scientific inquiry and can effectively pass on appropriate knowledge and skills to their students. This is often not the case due to the nature of university-level instruction that is often didactic. Scientific inquiry processes, if formally addressed at all, are often treated as an amalgam of non-hierarchical activities. There is a critical need to synthesize a framework for more effective promotion of inquiry processes among students at all levels. The author presents a new hierarchy of teaching practices and intellectual processes with examples from buoyancy that can help science teachers, science teacher educators, and curriculum writers promote an increasingly more sophisticated understanding of scientific inquiry among students.

The strength of a concept rests in its ability to organize information. What at first appears to be a disorganized body of knowledge is made comprehensible and useful when a unifying framework is developed. Scientific inquiry is often presented as a jumble of disorganized but interrelated procedures. Teachers and teacher candidates are regularly encouraged to use inquiry processes in demonstrations, lessons, and labs, but there is little organizational pattern provided to relate inquiry to these approaches. This often leaves teachers and teacher candidates with questions about differences between demonstrations, lessons, and labs, and what role inquiry plays in each. For instance, couldn't a good lesson consist of an interactive demonstration? If so, how would the interactive demonstration differ from a lesson? A good lab activity would seem to be a good lesson. So, what is the difference between a lesson and a lab activity? The differences between demonstrations and labs seem readily apparent; the real problem resides in defining the transitional phase between a demonstration and a lab – the lesson. Clearly, there must be identifiable differences between all such activities, but science education literature in this area appears to make no clear distinction between them with but a few rare exceptions. (See for instance Colburn, 2000; Staver & Bay, 1987.)

Student inquiry has been defined in the *National Science Education Standards* (NAS, 1995, p. 23) as "the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world." (It is to this definition that the author refers when he mentions "inquiry-oriented" activities.) The *Standards* do define the abilities necessary for students to conduct scientific inquiry: "identify questions and concepts that guide scientific investigations, design and conduct scientific investigations, use technology and mathematics to improve investigations and communications, formulate and revise scientific explanations using logic and evidence, recognize and analyze alterative explanations and models, [and] communicate and defend a scientific argument" (pp. 175-176). Nonetheless, the *Standards* provide precious little guidance about how inquiry processes are to be taught. It evidently is assumed that once a teacher candidate learns how to conduct inquiry in the university setting (often a poor assumption given the generally didactic nature of science instruction) that procedural knowledge will somehow flow from the teacher to his or her students. This is much akin to the incorrect assumption that problem-solving skills can be readily learned through observation of numerous examples. At least one case study shows that this is not always the case (Wenning, 2002). The literature of scientific literacy is replete with calls for teachers to use inquiry as a regular part of teaching practice. Unfortunately, this doesn't always happen. One of the chief reasons cited in the literature about the failure of science teachers to implement inquiry practice is that the teachers themselves are inadequately prepared to use it (Lawson, 1995). Again, science education literature appears to be largely devoid of information about how one actually goes about teaching inquiry skills – arguably one of the most central goals of science teaching.

Merely speaking with teacher candidates about random inquiry processes will not help them teach in such a way that will systematically lead to their students becoming scientific inquirers. A hierarchy must be provided for effective transmission of this knowledge. Failure to do so can result in undesirable consequences. For instance, the author's recent experience with a secondary-level student teacher resulted in the revelation of a significant pedagogical problem. The student teacher was supposedly well prepared to use various inquiry processes with his high school physics students, but his teaching practice resulted in confusion. The physics students being taught were rather new to inquiry, the cooperating teacher having used more of a didactic approach with traditional lecture and "cookbook" labs prior to the student teacher's arrival. The student teacher gave his students a clear performance objective, provided the students with suitable materials, and essentially told them to "do science." The students leapt out of their seats and moved into the lab with joyful anticipation. After about 15 minutes of lab activity it became obvious to both the student teacher and the university supervisor that the students were floundering. One student called out, "This is a waste of time!" Another vocalized, "We don't know what's going on." Yet another blurted, "We need some help over here." It turned out that the students had no idea how to "do science" at the specified level. It became clear to the teacher educator that this student teacher needed to know more about how to teach students to "do" science.

This article originated as a result of discussions held during a subsequent seminar with several student teachers. One of the student teachers (not the one in the example) pointed out rather succinctly that there is a difference between a lesson and a lab – that the teacher will mostly control a lesson whereas the lab would be mostly controlled by the student. At this point it became evident to the author that student teachers – indeed all science teachers – must have a comprehensive understanding of the hierarchical nature and relationship of various pedagogical practices and inquiry processes if they are to teach science effectively using inquiry.

Because inquiry processes are the "coin of the realm" for science teachers, pertinent activities in relation to pedagogical practices must be clearly delineated. Science teacher educators should be interested in not only inculcating an understanding of inquiry in teacher candidates, they should also want to make sure that teacher candidates are able to actually teach in a way that their future students will come to know and understand the nature of scientific inquiry. If one is to follow conventional wisdom, teachers who attempt to teach inquiry processes should progress through a series of successively more sophisticated levels of pedagogical practice, each having associated with it increasingly complex inquiry processes. They will repeatedly model appropriate actions, and then fade from the scene allowing students to implement the modeled inquiry processes.

Basic Hierarchy of Pedagogical Practices – Based on the earlier work of Colburn (2000), Staver and Bay (1987), and Herron (1971), the author here proposes a more extensive continuum to delineate the levels of pedagogical practice and offer some suggestions as to the nature of associated inquiry processes. Table 1 shows various inquiry-oriented teaching practices in relation to one another. It should be noted from the table that levels of inquiry differ primarily on two bases: (1) intellectual sophistication, and (2) locus of control. The locus of control shifts from the teacher to the student moving from left to right along the continuum. In discovery learning the teacher is in nearly complete control; in hypothetical inquiry the work depends almost entirely upon the student. Intellectual sophistication likewise increases continuously from discovery learning through hypothetical inquiry. The thought processes required to control an activity are shifted from the teacher to the student as practices progress toward the right along the continuum. As will be seen, inquiry labs, real-world applications, and hypothetical inquiry can be subdivided further.

In the following sections, each of the above practices will be operationally defined; in a corresponding sidebar story, each will be described for ease of reading and as a way of providing additional insights. The author will use a common topic from physics – buoyancy – to describe how different levels of pedagogical practice can be deployed to address this important physical topic, to effectively promote learning of inquiry processes, and to teach various intellectual process skills.

SIDEBAR STORY 1: Example of Discovery Learning – In this activity, students are first questioned about the phenomenon of buoyancy. They are asked to recollect certain everyday experiences, say, while swimming and manipulating such things as beach balls or lifting heavy submerged objects such as rocks. If students have not had such experiences, they are asked to submerge a block of wood under water. They perceive the presence of a "mysterious" upward or buoyant force. They then can be led with effective questioning strategies and instructions to develop the concept of buoyant force. The teacher might then present one or more guiding questions relating to sinking and floating, "What determines whether an object floats or sinks in water?" The teacher provides students with objects of varying density, suggesting ways to use them. Perhaps the objects are labeled with density values if the students have already developed an understanding of the concept. Various objects are then placed in a container filled with water. Some sink, others float. The students are asked to state a relationship between the densities of the objects and whether or not they sink or float in water. If provided with the density of water, students can generate a more concise statement of sinking and floating – that objects with densities less than that of water float in water whereas objects with densities greater than that of water sink in water. Alternatively, students conclude that objects with densities of less than one float in water, whereas objects with densities greater than one sink in water.

Discovery Learning – Discovery learning is perhaps the most fundamental form of inquiry-oriented learning. It is based on the "Eureka! I have found it!" approach. The focus of discovery learning is not on finding applications for knowledge but, rather, on constructing concepts and knowledge from experiences. As such, discovery learning employs reflection as the key to understanding. The teacher introduces an experience in such a way as to enhance its relevance or meaning, uses a sequence of questions during or after the experience to guide students to a specific conclusion, and questions students to direct discussion that focuses on a problem or apparent contradiction. Employing inductive reasoning, students construct simple relationships or principles

Discovery Learning	Interactive Demonstration	Inquiry Lesson	Inquiry Lab	Real-world Applications	Hypothetical Inquiry
Low		**Intellectual Sophistication**			**High**
Teacher		**Locus of Control**			**Student**

Table 1. *A basic hierarchy of inquiry-oriented science teaching practices. The degree of intellectual sophistication and locus of control are different with each approach.*

from their guided observations. Discovery learning is most frequently employed at the elementary school level, but at times it is used even at university level. See sidebar story 1 for an example of discovery learning.

Interactive Demonstration – An interactive demonstration generally consists of a teacher manipulating (demonstrating) a scientific apparatus and then asking probing questions about what will happen (prediction) or how something might have happened (explanation). The teacher is in charge of conducting the demonstration, developing and asking probing questions, eliciting responses, soliciting further explanations, and helping students reach conclusions on the basis of evidence. The teacher will elicit preconceptions, and then confront and resolve any that are identified. The teacher models appropriate scientific procedures at the most fundamental level, thereby helping students learn implicitly about inquiry processes. See sidebar story 2 for an example of an interactive demonstration.

Inquiry Lesson – In many ways the inquiry lesson is similar to the interactive demonstration. However, there are several important differences. In the inquiry lesson, the emphasis subtly shifts to a more complex form of scientific experimentation. The pedagogy is one in which the activity is based upon the teacher remaining in charge by providing guiding, indeed leading, questions. Guidance is given more indirectly using appropriate questioning strategies. The teacher places increasing emphasis on helping students to formulating their own experimental approaches, identifying and controlling variables, and defining the system. The teacher now speaks about scientific process explicitly by providing an ongoing commentary about the nature of inquiry. The teacher models fundamental intellectual processes and explains the fundamental understandings of scientific inquiry while the students learn by observing and listening, and responding to questions. This is in effect scientific inquiry using a vicarious approach with the teacher using a "think aloud"

SIDEBAR STORY 2: Example of Interactive Demonstration – Students then are asked to press down on a floating object. They experience the upward buoyant force. If students are careful observers, they can see that buoyant force increases as more and more of the volume of the floating body is submerged in the water. Once the object is entirely submerged, the buoyant force appears to become constant. For floating objects held entirely immersed in water the buoyant force is greater than their weight. When such objects are released, they float upward until their weight is precisely counterbalanced by the buoyant force; the object is then in an equilibrium state.

A guiding question might be, "What is the relationship between the weight of an object suspended in air, the weight of that object suspended in water, and the buoyant force?" The teacher, for the sake of simplicity, then restricts the discussion to sinking objects, then brings out a small spring scale and asks how the spring scale might be used to measure the buoyant force on a sinking object. Clearly, the buoyant force appears to operate in the upward direction, but that the object in question still has a propensity to sink when suspended in water. If the students are familiar with force diagrams, they might quickly conclude that for objects that sink, the weight is greater than the buoyant force.

With appropriate questioning, the teacher can move the discussion from one that is purely qualitative (conceptual) to one that is more quantitative. Eventually, the students realize that the buoyant force (F_b) for sinking objects is the difference between the weight of the object in air (W_a) and the weight of the same object when completely immersed in the fluid (W_f). This will then lead to the students concluding that the difference between these two values is the buoyant force. When asked to define that relationship mathematically, students will quickly respond by providing an equation similar to $F_b = W_a - W_f$ where a positive F_b is defined as acting in the upward direction. Students then use this relationship to find the buoyant force on a floating object. Consider the following "dialogue" in relation to this interactive demonstration. (For more details about this general approach see Gang, 1995.)

Note: Place a metal object on a spring balance with the object suspended in air above the surface of a container full of water.

Q. How can one determine the buoyant force experienced by an object submerged in a liquid?

Note: Following student responses, submerge the object entirely in water.

Q. Why is there a difference between weight of this object in air (W_a) and its weight when suspended in the fluid (W_f)?

Note: It's because of the buoyant force.

Q. How might we calculate the buoyant force due to the liquid given the object's weight in air and in water?

Note: $F_b = W_a - W_{f.}$ Next, slowly immerse a wooden object on a scale into the water. Read out the changing weight until it reaches zero.

Q. What is the buoyant force exerted on a piece of wood floating on the surface of the water?

Note: $F_b = W_a$ because $F_b = W_a - 0$

After this interactive demonstration, a series of questions is directed at students asking them to predict which physical factors affect buoyancy which they will later address in an inquiry lesson.

protocol. This approach will more fully help students understand the nature of inquiry processes. This form of inquiry lesson is essential to bridging the gap between interactive demonstration and laboratory experiences. This is so because it is unreasonable to assume that students can use more sophisticated experimental approaches before they are familiar with them. For instance, students must be able to distinguish between independent, dependent, controlled, and extraneous variables before they can develop a meaningful controlled scientific experiment. See sidebar story 3 for an example of an inquiry lesson.

Inquiry Labs – An inquiry lab is the next level of pedagogical practice. Inquiry labs generally will consist of students more or less independently developing and executing an experimental plan and collecting appropriate data. These data are then analyzed to find a law – a precise relationship among variables. This inquiry lab approach is not to be confused with the traditional "cookbook" laboratory activity. The distinction between traditional cookbook labs (sometimes called "structured inquiry") and true inquiry-oriented labs is profound. The major distinguishing factors are presented in Table 2.

Three Types of Inquiry Lab – Based initially on the work of Herron (1971), the author further suggests that inquiry labs can be broken down into three types based upon degree of sophistication and locus of control as shown in Table 3 – guided inquiry, bounded inquiry, and free inquiry. This table displays the shift of question/problem source and procedures as lab types become progressively more sophisticated. Each approach constitutes a stepwise progression of moving from modeling appropriate inquiry practice to fading from the scene. A guided

SIDEBAR STORY 3: Example of an Inquiry Lesson – Again turning to the topic of buoyancy, what might an inquiry lesson involving buoyancy look like? An example would be a teacher who asks the single guiding question, "What factors influence the amount of buoyancy experienced by an object that sinks?" In response, students provide a list of possible factors such as the density of immersing liquid, orientation of the object in liquid, depth of the object in liquid, and weight, composition, density, shape, size, and volume of the object. They then are asked to suggest ways to test whether or not each of these factors does indeed influence buoyancy. (At this point the teacher might want to restrict the discussion to the buoyant forces acting only on sinking objects for simplicity's sake, noting that work with floating objects will come later.)

Q. Which factor should we test first, and does it make a difference?

Note: It does make a difference. We must be able to control all variables. Depth would be a good place to start.

Q. Is the buoyant force exerted by a liquid dependent upon the depth? How might we test this?

Note: Check buoyant force at varying depths controlling for other variables.

Q. Is the buoyant force experienced by a submerged object related to its shape? How might we test this?

Note: Test with a clay object formed into different shapes.

Q. Does the buoyant force experienced by a submerged object depend on its orientation? How might we test this?

Note: Test with a rectangular metallic block oriented along three different axes.

Q. Is the buoyant force experienced by a submerged object related to its volume? How might we test this?

Note: Test using two different sized objects of the same weight.

Q. Is the buoyant force exerted on a body dependent upon the weight of an object? How might we test this?

Note: Test with aluminum and copper ingots of identical volume.

Q. From what you've seen, does the buoyant force depends upon the density of an object?

Note: It does not.

Q. Is the buoyant force exerted by a fluid dependent upon the density of the liquid? How might we test this?

Note: Test using liquids of different density such as fresh water, alcohol, oil, glycerin, and honey.

As the steps of this inquiry lesson are carried out, the teacher makes certain that proper experimental protocols are observed such as the control of variables (e.g., one independent and one dependent variable tested at one time). This will require that certain of the above experiments be conducted in proper relative order. (For instance, the shape or orientation tests might be affected by depth if depth isn't first ruled out.) There is a regular discussion of scientific methodology, making students aware of the procedures of a controlled experiment. Once the factors that significantly affect buoyancy are identified, students will next design and carry out an inquiry lab to determine the actual relationships between buoyancy and those factors empirically shown to be related to the buoyant force – density of the immersing liquid and the volume of the object immersed.

Cookbook labs:	Inquiry labs:
are driven with step-by-step instructions requiring minimum intellectual engagement of students thereby promoting robotic, rule-conforming behaviors.	are driven by questions requiring ongoing intellectual engagement using higher-order thinking skills making for independent thought and action.
commonly focus students' activities on verifying information previously communicated in class thereby moving from abstract toward concrete.	focus students' activities on collecting and interpreting data to discover new concepts, principles, or laws thereby moving from concrete toward abstract.
presume students will learn the nature of scientific inquiry by "experience" or implicitly; students execute imposed experimental designs that tell students which variables to hold constant, which to vary, which are independent, and which are dependent.	require students to create their own controlled experimental designs; require students to independently identify, distinguish, and control pertinent independent and dependent variables; promote student understanding of the skills and nature of scientific inquiry.
rarely allow students to confront and deal with error, uncertainty, and misconceptions; do not allow students to experience blind alleys or dead ends.	commonly allow for students to learn from their mistakes and missteps; provide time and opportunity for students to make and recover from mistakes.
employ procedures that are inconsistent with the nature of scientific endeavor; show the work of science to be an unrealistic linear process.	employ procedures that are much more consistent with authentic scientific practice; show the work of science to be recursive and self-correcting.

Table 2. *Some major differences between traditional cookbook and authentic inquiry-oriented lab activities.*

inquiry lab is the next level of inquiry practice beyond the inquiry lesson. The guided inquiry lab, like the bounded inquiry lab to follow, is a transitional form of lab activity leading ultimately to the free inquiry lab approach in which students act with complete independence – even to the point of identifying the research question or problem to be solved. With each successive approach, the teacher provides less structure, and the students become more independent in both thought and action.

Guided Inquiry Lab – The guided inquiry lab is characterized by a teacher-identified problem and multiple leading questions that point the way to procedures. A guided inquiry lab might be prefaced by a pre-lab activity or discussion. In guided labs, students are provided with a clear and concise student performance objective. For instance, "Find the relationship between force and acceleration." or "Determine how the magnetic field strength varies as a function of distance from a current-carrying wire." or "Find the relationship between work and energy in this system." or "Gather empirical evidence from a pendulum to determine whether or not energy is conserved in the relationship between gravitational potential energy and kinetic energy." Then, as students progress through the lab, they follow a series of leading questions in order to achieve the goal of the lab. While the guided inquiry lab can and must be considered a transitional form between the inquiry lesson and more advance forms of inquiry, it is not sufficient as a complete transitional form. Again, teachers must model more advanced forms of inquiry and then fade, providing and then gradually remove scaffolding, as students become better inquirers after scientific knowledge.

Bounded Inquiry Lab – Students are presented with a clear and concise student performance objective associated with a concept, but they are expected to design and conduct an experiment without the benefit of a detailed pre-lab or written leading questions. They might be required to make simple observations about the relationship between variables, and then asked to perform a dimensional analysis as a means for formulating a logical basis for conducting an experiment. A pre-lab might still be held, but it would focus on non-experimental aspects such as lab safety and use and protection of laboratory equipment. Students are entirely responsible for experimental

Inquiry Lab Type	Questions/Problem Source	Procedures
Guided inquiry	Teacher identifies problem to be researched	Guided by multiple teacher-identified questions; extensive pre-lab orientation
Bounded inquiry	Teacher identifies problem to be researched	Guided by a single teacher-identified question, partial pre-lab orientation
Free inquiry	Students identify problem to be researched	Guided by a single student-identified question; no pre-lab orientation

Table 3. *Distinguishing characteristics of inquiry labs by type.*

design, though an instructor might provide assistance as needed in lab; this assistance is more in the form of asking leading questions rather than providing answers to student questions. Note that before a bounded inquiry lab is conducted, students must have had considerable experience with the guided inquiry lab. Without having a model to follow, students might be confounded in bounded labs by a general lack of direction when told to "do science." This can lead to the frustration and lack of student engagement experienced by the student teacher in the situation described in the outset of this article. See sidebar story 4 for an example of a bounded inquiry lab.

Free Inquiry Lab – Both the guided inquiry and bounded inquiry labs will start off with a teacher-identified problem as well as all or part of the experimental design. This contrasts with the free inquiry lab in which students identify a problem to be solved and create the experimental design. Free inquiry labs most likely will be closely associated with a semester-long or capstone science project. They are great outlets for gifted students. More than likely, free inquiry labs will be conducted outside of regular class time, or in a class composed of gifted or otherwise more advanced students.

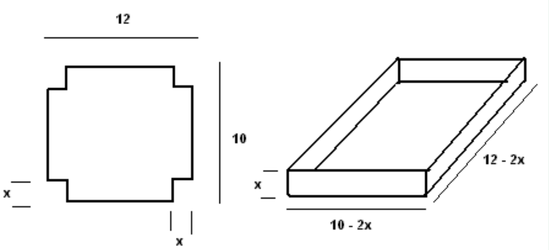
SIDEBAR STORY 4: Example of a Bounded Inquiry Lab – As a follow-up activity of the inquiry lesson, students conduct a bounded inquiry lab in which they are provided with questions but are free to develop the lab experiments as they see fit. (This approach assumes that students are already familiar with experimental design from prior experiences.) From the inquiry lesson, students will have found that both the volume of the immersed object and the density of the immersing fluid have a significant affect on buoyancy. There are really two questions that now need to be addressed: (1) What is the relationship between buoyant force and the volume of an object? and (2) What is the relationship between the buoyant force an object experiences and the density of the fluid in which it is immersed? These two questions can be split among several groups using a "jigsaw" approach that allows for showing the nature of the scientific endeavor as a community effort and as self-correcting. Once answers to these questions are determined, results can be compared and integrated into a whole as noted below.

The group(s) working on question (1) will find that the buoyant force is directly proportional to volume; the group(s) working on question (2) will find that buoyant force is directly proportional to the density of the fluid. When these relationships are brought together, it is clear that $F_b \propto \rho V$. Similarly, $F_b = k\rho V$ where an analysis of the units shows that k's units are those of acceleration. Using known values of F_b, ρ, and V, k can be shown to be 9.8. Hence, $k = 9.8\text{m/s}^2 = g$. The general form of the buoyancy relationship is then found to be $F_b = \rho V g$.

Real-world Applications – In this next level of inquiry teaching, students apply what they have learned through experience to new situations. They find answers related to authentic problems while working individually or in cooperative and collaborative groups using problem-based & project-based approaches. While textbooks dealing with the subject matter of buoyancy typically will have a plethora of end-of-chapter problems for the students to work, solving such problems alone does not demonstrate to students how information about buoyancy is actually used by scientists and engineers to solve complex problems. Including problem-based and project-based activities at this point will serve to show the utility of what has been learned to date. See sidebar story 5 for an example.

SIDEBAR STORY 5: Example of a Real-world Application using a Project-based Approach – A teacher poses a question to the students, "Given a rectangular sheet of metal, how should it be shaped in order to carry the maximum possible load when set in water?" The students are then challenged to work in small groups to solve this problem, build "boats" from the supplied metal, and then test their load-bearing capacity by placing weights in a floating boat to the point that it sinks. Clearly, the problem is to develop a boat with maximum volume because maximum volume will produce the greatest buoyant force according to the relationship $F_b = \rho V g$. This is due to the fact that the density of the water and acceleration due to gravity are fixed.

The teacher then provides students with a thin sheet of metal measuring 12 inches by 10 inches to be used to make an open box. Squares of equal sides "x" are cut out of each corner and then the sides are folded and sealed to make a water-tight box as shown in the figure below.



Using guidance from the teacher as necessary, students work out a solution for the maximum volume of the box as follows:

$V = L * W * H$
$L = 12in - 2x$
$W = 10in - 2x$
$H = x$ where $0 < x < 5$

Volume then can be written (ignoring units temporarily)

$V(x) = (12 - 2x)(10 - 2x)(x)$ or
$V(x) = 4x^3 - 44x^2 + 120x$

Students then make a plot of V(x) versus x and examine the extrema (or find zeros of the derivative if they know how) to find the maximum volume. Solution: x = 1.81*in*

SIDEBAR STORY 6: Example of Pure Hypothetical Inquiry – One example of pure hypothetical inquiry in relation to the current topic, buoyancy, would be to address the source of the buoyant force. The student hypothesizes that buoyancy results from differences in pressure applied over various surface areas (hence forces), say, on the top and bottom of an imaginary cube. With an understanding that pressure increases with depth in a fluid ($P = \rho g d$) and that force equals pressure per unit area multiplied by the area under consideration ($F = PA$), a student can use the imaginary cube to explain the origin of the buoyant force. Calculating pressure on horizontal parallel surfaces at two different depths and taking the difference results in a correct formulation of the buoyant force. This provides support for the correctness of the explanatory hypothesis.

$$F_{top} = P_{top}A = \rho g d_{top} A$$
$$F_{bot} = P_{bot}A = \rho g d_{bot} A$$
$$F_b = F_{bot} - F_{top} = \rho g (d_{bot} - d_{top}) A$$
$$F_b = \rho g V$$

A reformulation of the last equation and proper identification of terms will show why Archimedes' principle works the way it does:

$$F_b = \rho g V = (\rho V) g = m_f g$$

where the subscripted *m* is the mass of the fluid displaced.

As a result of this form of pure inquiry, the student has deduced from a hypothetical construct the empirical form of the buoyant force law, and can explain Archimedes' law. The student has moved from mere knowledge to understanding. Now, to make certain that students understand the relationship between pure hypothetical inquiry and experimentation (and ultimately theory), they should then be asked to use the hypothesis to explain other real-world phenomena. For instance, how does the hypothesis that buoyant force results from a pressure differential on a body account for such things as floating objects, thermal convection, plate tectonics, and the workings of a Galilean thermometer?

Because this level of inquiry is the most advanced, it is unlikely that many high school students will reach this point along the continuum. Nonetheless, high school physics teachers might want to take the opportunity to have gifted students use this approach to explain empirical laws and apply their hypotheses to other real world phenomena. Alternatively, science teachers might want to use applied hypothetical inquiry in any of its most rudimentary forms – problem-based learning, technological design, failure analysis, and some forms of experimentation – to reach this level.

Hypothetical Inquiry – The most advanced form of inquiry that students are likely to deal with will be hypothesis generation and testing. Hypothetical inquiry needs to be differentiated from making predictions, a distinction many physics teachers fail to understand or to make with their students. A prediction is a statement of what will happen given a set of initial conditions. An example of a prediction is, "When I quickly increase the volume of a gas, its temperature will drop." The prediction has no explanatory power whatsoever, even though it might be a logical deduction derived from laws or experiences. A hypothesis is a tentative explanation that can be tested thoroughly, and that can serve to direct further investigation. An example of a hypothesis might be that a flashlight fails to work because its batteries are dead. To test this hypothesis, one might replace the supposedly bad batteries with fresh batteries. If that doesn't work, a new hypothesis is generated. This latter hypothesis might have to do with circuit continuity such as a burned out light bulb or a broken wire. Hypothetical inquiry deals with providing and testing explanations (usually how, rarely why), to account for certain laws or observations. Hypotheses most certainly are not "educated guesses."

Two Types of Hypothetical Inquiry – Like with inquiry labs, hypothetical inquiry can be differentiated into basic forms – pure and applied – each associated with its own type of pedagogical practices and inquiry processes. Like pure and applied science, pure and applied hypothetical inquiry differ. Pure hypothetical inquiry is research made without any expectation of application to real-world problems; it is conducted solely with the goal of extending our understanding of the laws of nature. Applied hypothetical inquiry is geared toward finding applications of prior knowledge to new problems. The two types of hypothetical inquiry essentially employ the same intellectual processes; they tend to differ on the basis of their goals. They are not otherwise distinguished in the hierarchy of pedagogical practices.

Pure Hypothetical Inquiry – In the current pedagogical spectrum, the most advanced form of inquiry will consist of students developing hypothetical explanations of empirically derived laws and using those hypotheses to explain physical phenomena. Pure hypothetical inquiry might address such things as why the intensity of light falls off with the inverse square of distance, how conservation of energy accounts for certain kinematic laws, how the laws for addition of resistance in series and parallel circuits can be accounted for by conservation of current and energy, and how Newton's second law can account for Bernoulli's principle. In the current set of examples dealing with buoyancy, a teacher could ask students to explain from a physical perspective how the buoyant force originates. By extension, the students might attempt to explain Archimedes' Principle – that the buoyant force is the equivalent to the weight of the fluid displaced. Questions such as these will lead to hypothesis development and testing. Through this form of inquiry, students come to see how pure hypothetical reasoning – the worth of which is attested to by successful application – becomes theory. See sidebar story 6 for an example of pure hypothetical inquiry.

SIDEBAR STORY 7: Examples of Applied Hypothetical Inquiry – After students have developed an understanding of the law of buoyancy, this knowledge can be applied to new situations as part of the process of hypothetico-deductive reasoning. For instance, students can be asked to determine the relationship between the buoyant force and the weight of the water displaced by the immersed object. The students will find and should be able to account for the fact that the buoyant force is equal to the weight of the fluid displaced by the immersed object. This is nothing more than Archimedes' principle.

Students also can apply their knowledge of the law of buoyancy to new situations in an effort to account for various observations such as the following: A beaker filled with water is placed on a balance. If an object that sinks is completely immersed in the water and suspended without allowing it to touch the bottom, how will the weight of the beaker with water-be affected? If the object is allowed to settle to the bottom, how will the weight of the system be affected?

Other questions about buoyancy can be introduced, and students allowed to work out explanations or make predictions. For example, a demonstration is conducted with objects that have densities greater or less than water. They are immersed in water and it is found that those objects that have a density less than water float and those objects with a density greater than water sink. Why do objects float or sink based on their density in comparison to the water? Students should be able to use the law of buoyancy to explain why.

What fraction of a fresh water iceberg is visible above the surface of a sea of salt water? A knowledge of the relative densities of the ice and water and the buoyant force being a function of the volume of water displaced by the ice should help solve the problem and for a prediction to be made.

Why does a Cartesian diver sink or rise when the pressure on the water increases and decreases respectively? Again, using the law of buoyancy and the principle of sinking or floating as a function of the densities of object and fluid can lead to the proper solution of this problem.

Applied Hypothetical Inquiry – Hypothetico-deductive reasoning can be fruitfully employed to account for certain observations or to make predictions. For instance, this approach can be used to develop concepts dealing with Archimedes' principle, the relationship of density to floating and sinking, and other related phenomena. Used this way, applied hypothetical inquiry can still overlap to a considerable extent with pure hypothetical inquiry. See sidebar story 7 for several examples of applied hypothetical inquiry.

Complete Hierarchy of Pedagogical Practices – Table 4 provides a more complete hierarchy of inquiry-oriented science teaching practices that includes distinctions between laboratory types and types of hypothetical inquiry. The continuum is now shown as a tuning-fork diagram with a long handle and two short tines. In addition to a progression of intellectual sophistication and locus of control, there are also other progressions along the continuum such as a shifting emphasis from concrete observation to abstract reasoning, from inductive processes to deductive processes, and from observation to explanation. In order to address these more fully, it is important to describe a hierarchy of inquiry processes associated with the continuum.

Hierarchy of Inquiry Processes – As has been stated, the degree of intellectual sophistication increases the further to the right along the continuum an inquiry practice is located. A question may now be logically asked, "What is the precise nature of this increasing intellectual sophistication?" Sophistication has to do with the type of the intellectual science process skills required to complete a specified level of inquiry-oriented activity. Some science educators (notably Ostlund, 1992; Lawson, 1995; Rezba et al., 2003) have distinguished two hierarchies of such intellectual process skills based on elementary/middle school and middle/high school education. The National Research Council (NRC, 2000) in its publication *Inquiry and the National Science Education Standards* identifies three sets of fundamental abilities of inquiry based on grade levels 1-4, 5-8, and 9-12. Regardless of these distinctions, people continue to use and develop all levels of intellectual process skills throughout their lives. Because most of the science reform movement literature has focused on less sophisticated inquiry skills, it seems that more advanced process skills are being overlooked. Clearly, if students are to be more critical thinkers, they probably should possess *advanced inquiry skills.* Advanced inquiry skills are those intellectual processes that might be said to represent the end-goal of science education (scientific literacy). A hierarchy of inquiry processes can be found in Table 5. The listings are intended to be suggestive, not definitive.

Application to Teacher Preparation, Instructional Practice, and Curricular Development – Given these hierarchical distinctions for the construction of scientific knowledge, it should now be clear what the student teacher's problem was in the example cited near the beginning of this article. The student teacher had moved from a series of low sophistication, teacher-centered inquiry activities – basically a series of interactive demonstrations – to a bounded lab activity that had a student-centered locus of control and a relatively high degree of sophistication. He moved from a situation in which the students were strongly dependent upon the teacher providing guidance to one with little to no guidance without first providing appropriate bridging activities. The only prior experiences the high school students had had in a lab setting prior to the arrival of the student teacher were traditional cookbook labs. These had left the students uninformed about important inquiry processes. The students, not having learned to "walk before they were asked to run," understandably had problems with the more advanced nature of the lab imposed upon them. The source of the student teacher's problem was that inquiry lessons and guided inquiry labs had not been a regular part of the students' physics curriculum before being confronted with a relatively sophisticated bounded inquiry lab; neither had attention been paid to the continuum of intellectual process skills so important to developing scientific inquiry. This was due in large part to the failure of the student teacher to understand the underlying hierarchies of pedagogical practices and inquiry processes. It was also the fault of this teacher candidate's educators to recognize and make known to him the underlying hierarchies of pedagogical practices and inquiry processes. That deficiency in the preparation of physics teacher candidates at Illinois State University has now been remediated.

The insights gleaned from the development of this paper have been infused throughout the physics teacher education curriculum at Illinois State University. When working with teacher candidates, the relationship between the practices of demonstration, lesson and lab and their associated intellectual processes is now being made explicit. Teacher candidates are developing a growing understanding of what it means to bridge the gap between teacher-centered activities and student-centered demonstrations, lessons and labs. Eventually all teacher candidates at Illinois State University will read and discuss this paper as part of a senior-level methods course. It is believe that this will redound to their benefit and their students for years to come.

There is a lesson here, too, for in-service teachers and curriculum developers. In-service teacher will greatly improve their practice by incorporating an understanding of levels of inquiry, and their students will directly benefit from a more effective form of teaching practice. Instructional development and curricular decision-making will likewise benefit from an understanding and application of the continuum of pedagogical practices and inquiry processes. Failure to include due consideration for the continuum at any level will in all likelihood result in a pedagogy that will be less effective both in theory and practice. Failure to do so will leave teacher candidates, and perhaps their future students, with an incomplete understanding of how to effectively teach science as both product *and* process.

Discovery Learning	Interactive Demonstration	Inquiry Lesson	Guided Inquiry Lab	Bounded Inquiry Lab	Free Inquiry Lab	Real-world Applications	Pure Hypothetical Inquiry Applied Hypothetical Inquiry
Low			**Intellectual Sophistication**				**High**
Teacher			**Locus of Control**				**Student**

Table 4. *A more complete hierarchy of inquiry-oriented science teaching practices including distinctions between laboratory types, and pure and applied inquiry.*

Rudimentary Skills	**Basic Skills**	**Integrated Skills**	**Advanced Skills**
Observing Collecting and recording data Drawing conclusions Communicating Classifying results Measuring metrically Estimating Decision making 1 Explaining Predicting	Identifying variables Constructing a table of data Constructing a graph Describing relationships between variables Acquiring and processing data Analyzing investigations Defining variables operationally Designing investigations Experimenting Hypothesizing Decision making 2 Developing models Controlling variables	Identifying problems to investigate Designing and conducting scientific investigations Using technology and math during investigations Generating principles through the process of induction Communicating and defending a scientific argument	Solving complex real-world problems Synthesizing complex hypothetical explanations Establishing empirical laws on the basis of evidence and logic Analyzing and evaluating scientific arguments Constructing logical proofs Generating predictions through the process of deduction
Low	**Intellectual Sophistication**		**High**

Table 5. *Relative degree of sophistication of various inquiry-oriented intellectual processes. These listings are intended to be suggestive, not definitive.*

The author wishes to thank Mr. Luke Luginbuhl for drawing the initial distinction between inquiry lesson and inquiry lab that served as the basis for this article. He was a 2004 graduate of the Physics Teacher Education program at Illinois State University. He now teaches physics at Havana High School in Havana, Illinois. He was not the student teacher mentioned in this article.

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