“Reading an object”: Developing effective scientific inquiry using student questions

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Abstract :
We explore the power of allowing students to construct their own conceptual understanding as they “read an object” in a series of guided inquiry steps, developing their own questions about the object. Their ownership of questions increases the learner’s engagement and results in more efficacious learning and meets the standards of quality intellectual work and meaningful lifelong learning, as opposed to school-based “mastery learning” for the test.

Keywords: problem-solving, critical thinnking engagement, guided inquiry, practice standards

Introduction

The National Inquirer Newspaper reports may be the antithesis of science; however, their motto “Inquiring minds want to know!” expresses what makes scientists tick. This passion for inquiry is what tends to be missing from traditional science classrooms at all levels, leaving many adults at best disinterested and at worst dismissive of scientific findings.

The solution to this problem is ready to hand. One of the most effective ways to engage learners is to make them curious—to start with a story or a problem that triggers questions and conversations and to link the learning topic to the students’ previous experiences, especially those that resonate with their own interests (Hynes-Berry, 2011, Cooper et al, 2007, Engel, 1995). Once the interest is there, the teacher’s role shifts from force-feeding information to facilitating an inquiry that moves from teaching “about” science to engaging students in *scientific practice*. As the *Next Generation Science Standards* (2012) point out, we use the term “practices” instead of a term such as “skills” to emphasize that engaging in scientific investigation requires not only procedural skills but also conceptual understanding specific to each discipline.

The following eight practice standards defined by the NGSS framework shift the emphasis from teacher’s delivery of material to developing the students’ capacity to authentically engage in the scientific process. Whether or not they eventually go into science fields they will have the habits of mind and procedures that characterize life-long learning and a spirit of inquiry.

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analysing 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

We have been testing a process called "*reading an object*" that incorporates the practice standards; it grounds the inquiry or investigation is grounded in questions generated by the students in response to a problem situation, rather than having the teacher establish the nature of the problem and dictate the direction students are to take in solving it., Because, "reading an object" shifts the emphasis to the learners s processing and questions, the motivation for problem-solving and arriving at an answer felt by inquiring minds is also shifted to the students/learners. As happens in real world scientific investigations, questions, clarifications and conjectures is a collegial process, involving other students rather than dominated by the teacher.

After a brief discussion of the theoretical and experimental underpinnings of our "reading an object" approach, we present several examples of its use in primary, middle, secondary and college classrooms.

In this paper, we highlight a classification of types of questions that can engage learners in different levels of thinking and understanding. While related to Bloom's (1956) taxonomy, a "ladder of inquiry", introduced by Hynes-Berry (2011) sees different orders of thinking as a dynamic.

Furthermore, we link the learning process in any successful classroom to the many similarities of the self-motivation that appears in children's learning in play, in the personal motivation and guidance of research for and by students working towards advanced degrees, and in the motivations behind the searching for answers of inquiring minds of all ages in life. In all three cases the thirst (and enthusiasm) for learning must arise within the learner. This development of the "student thirst for learning" greatly reduces the tension between the present requirements of standardized achievement imposed on the nation's classrooms, and authentic learning taking place in those classrooms through an interactive hands-on, minds-on process. Ravitch (2001, 2010) has chronicled such tensions.

We have tested our "*reading an object*" procedure at several different grade levels, and we give examples used in K-2, middle school, high school college levels and with pre-service and in-service teachers. These examples show how "reading" simple objects can lead to learning at all levels in all areas of the curriculum, from early literacy to social science and to high school sciences. This process can be used in any grade and in any teaching area; plus, the objects themselves can be simple, familiar or unusual, complex, closely or seemingly unconnected to the topic that the teacher wants to pursue; although our process of reading an object has very distinctive guidelines, it is (and always should be) a very open student-sensitive process. Variants can include access to other materials - books, the internet, etc., but always generated from the minds and interests of the students themselves, and developed from the flow of student questioning and understanding.

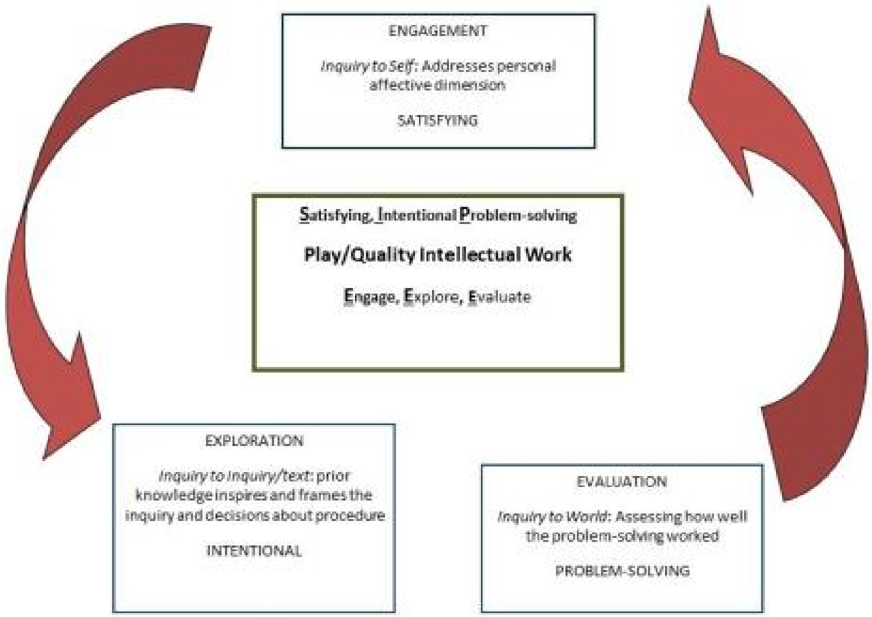

Figure 1. Quality Intellectual Work – the connections, adapted from Hynes-Berry (2011)

Background to the "reading an object" method; good things come in THREES:

In our exploration of what it means to teach for understanding in the interest of developing and supporting life-long learning, we have introduced a few principles. An important factor driving these principles is the goal of *quality intellectual work* taking place in every classroom. This concept introduced by Newman (1996) incorporates the definition for authentic learning; our principles help to define the roles of the actual interactions taking place in such classrooms between the students and teachers and between the students and the teacher(s).

Learning at the most fundamental level comes from the brain's *need-to-know*. The impulse to learn comes from a wide spectrum of conditions, from answering a "fight or flight" question to cultural and social considerations, to the habit of curiosity, (intellectual or otherwise) or simple delight (in learning). A successful classroom enhances the positive disposition to learning revealing its benefits, immediate and longer range, to the learner. When the learner owns the learning through intrinsic problem-solving, as opposed to an extrinsic rewards system, the learning is more likely to move from the brain's pre-frontal cortex into long term memory (Wood et al, 2011).

Play (Bruner et al, 1976, Elkind, 2007), scientific research and authentic classroom learning Newman (1996) utilize the same characteristics and procedures of self-motivations in learning. Note that the term "play" is very specific: defined as "play is children's work" by Bruner (1987) and discussed by other researchers in cognition and education: Hirsh-Pasek et al (2009), Katz and Thomas (2003), Paley (2005), Lillard et al (2013) - see Hynes-Berry (2011), chapter 4, for further detailed analysis. Also note that by "research", we are specifically referring to the typically 3 to 6 year-long student Ph.D. thesis process of defining a project, researching the project, and finally presenting the results of the project to the outside world - to a thesis committee and beyond. We have defined the **SIP** principle [***S**atisfying, **I**ntentional **P**roblem-Solving*] (Hynes-Berry, 2011) in describing an effective classroom which uses these characteristics to reach this goal of quality intellectual *student* work.

- ***Satisfying:*** the quality intellectual work must be engaging, intrinsically rewarding, and develop competence and confidence *for the student*

- ***Intentional:*** *students* constructing models and strategies leading to the students' realization that they are building competence
- ***Problem-solving:*** students developing their own progress milestones, accomplishing them and explaining their own achievements.

Figure 1 (adapted from page 164 of Hynes-Berry, 2011) shows the dynamics and connections of these relationships as they lead to students engaged in quality intellectual work.

The follow-up **PIP** principle [***Problem-setting, Investigating, and Problem-solving***] is a three part cycle that underlies an effective guided inquiry classroom (Hynes-Berry, 2011, Kuhlthau et al, 2007, McDermott, 1996, NRC, 2000, NRC, 2007), as well as the ideas of the *Scientific Method.* This principle corresponds closely to the E's of Engagement, Exploration, and Evaluation discussed by Bybee (2002) and Klentschy and Thompson (2008), and familiar to many teachers at all grade levels.

- ***Problem-setting*** develops the student interest and engagement in an inquiry that has personal meaning so that there is a positive disposition to work towards an answer; the group discusses and more closely defines the exact nature of the problem, stressing that it must be "set" in terms that are actionable.

- ***Investigation*** calls for ***exploration*** that is guided by prior knowledge both about the topic of inquiry, often including a prediction or estimate; the learners work in small groups to produce data using methodology appropriate to the discipline. The data are then analysed and synthesized. The students' ideas, plans, and later their data and analyses, are recorded in their own notebooks - these become their record of learning, and can be a valuable assessment tool for themselves and for the teacher.

- ***Problem-solving*** necessarily includes ***evaluation***-- analysing and assessing how well the solution arrived at satisfies the problem that was set. Each student group shares its synthesis and analysis of the data used to solve the problem(s). This leads to a full group discussion exploring questions such as: "Is this a sufficient answer to the problem?", "Are there new questions/problems to pursue?", or "Does the question need revising?", "Was there a problem with the investigation?" (e.g. identify new variables, refine data collection, use tools better or use better tools). Such questions are asked after any investigation, scientific or otherwise. Through this process, the students realize they have become investigative scientists, equipped with an approach they can apply to other learning experiences in life.

The specific "Modeling" curriculum in high school physics, chemistry and biology (The American Modeling Teachers Association, 2013; Hestenes, 2013) accentuates the group evaluative part of this approach as students provide group feedback and confidence-building often specifically in whiteboard presentation sessions.

For the students, all three parts must be **S**atisfying, **I**ntentional **P**roblem-solving (SIP) and throughout all three parts of the lessons we have: questions, questions, questions…

The role of Questions in promoting Quality Intellectual Work

The **C-P-S** principle defines the student learning cycle to begin with the ***Concrete***, move to the ***Pictorial*** and then to the ***Symbolic***; this cycle represents how learning moves from a lower level of comprehension to deeper understanding of how to analyse and visualise conceptual relationships and finally to the highest order thinking that involves synthesis and other abstract/symbolic forms of conceptual understanding. The different orders of thinking are not strictly hierarchical but are better understood as a ladder, whose rungs correspond to ***three levels of questions: closed, leading and open.***

We think this condensed version, shown in Table I, is easier to understand and interpret than the more commonly used pyramid of learning and comprehension as a Bloom taxonomy of questions (Bloom et al, 1956).

Table 1. The ladder of questions, level of inquiry and level of cognition

Level	Questions - Level of Inquiry		Development
3	Open	Evaluating/synthesizing	Abstract / symbolic
2	Leading	Analyzing/applying	Pictorial
1	closed/leading	Knowledge/comprehension	Concrete

Just to see and/or feel an object raises questions, memories and connections in the naturally inquisitive student mind - and these will be different for every student! An effective classroom harnesses these often disparate ideas to promote SIP learning. As Alison King (1995) asks: "If good questioners are good thinkers, then is the reverse true? Are good thinkers good questioners? Do inquiring minds really want to know?"

Moreover, effective inquiry is dynamic. It calls for flexibility in moving back and forth between the three levels and the three kinds of questions. The role of an effective teacher is guiding the learner's movement in a way that keeps the focus on the specific inquiry but that also gives them ownership in the questions and the exploration so that in the end they will also be evaluating the understanding that they see as an important take-away. Students come away having experienced ***S***atisfying ***I***ntentional ***P***roblem-solving and have themselves been engaged in clothing naked science facts to develop deep conceptual understanding.
"Reading an object" lessons can span the whole curriculum: they call for the teacher to identify beforehand the essential learning goals for the children: the overarching inquiry questions must be broken down to reflect the "big ideas" to be addressed; the sequence of activities in the classroom needs to build up to a culminating project, as the students learn by

- Inquiring, observing, reflecting, making sense of the world around them
- Being invested/engaged by a desire to understand questions which may span several disciplines or may use cross-cutting, unifying principles
- Formulating deeper questions based on the interactive investigative process

We encourage the reader to analyse how the example "reading an object" lessons which follow can generate deeper, open-ended questions coving a wide range of curriculum topics.

Some example "Reading an Object" lessons

1 – Mangos (tested at K-2, MS levels, in-service): What kinds of questions can we ask and what kind of questions can we answer in carrying out a guided inquiry? To develop competence in an area of inquiry (Murphy and Alexander, 2006), students must have a deep foundation of factual knowledge:

Factual, level 1 example questions for students to ask and to answer include:

- What kinds of mango are there?
- How long does a mango tree or bush live?
- What kind of plants produces mangos?
- Where do mangos grow?

Possible questions of this sort in other disciplines might include: What is place value in numbers? What are the body parts of an insect and how do they compare to the body parts of an arachnid?

Level 2 questions might include: what are some simple machines we use to move? Students should be able to relate these understandings to a strong conceptual framework.
Possible questions of this sort in other disciplines might include:
How does place value work when we are doing operations such as subtracting 672 from 486?
What does it mean to scientifically classify creatures, such as the making a distinction between creepy crawlies who are insects and those that are spiders?
What important roles can machines and tools play in scientific inquiry?

Level 3 questions might organize knowledge in ways that facilitate retrieval and application.
Our mango investigation illustrates how students should be able to ask and to work on answers to questions in each of the levels:

***Objectives and problem setting*:** Each student group receives a mango - note that several different types are available in the grocery stores, but most students have never seen a mango. Typical leading questions from the teacher or from the students are: What is a mango? Where does it come from? What does it taste like? Is it a strange apple?

The investigative process: The students explore the fruit - they are asked to feel free to cut it open and taste it; they use words and pictures to describe it. They record some questions raised by this activity - in their notebook or on the yellow post-its. Some of these questions can be answered in a whole class discussion, which ideally raises further level 1 and level 2 questions: How and where do they grow? - on trees, on bushes, underground, in Hawaii? Can we plant them in the classroom?

Now with their renewed attention, they are ready for a quiz: for example, they are shown six pictures of growing mango bushes (as in the figure for the cotton boll class in example 3), and asked to put them in a chronological order, a,b,c, ..etc - there are varying ways of presenting the results to help lead the discussion which should aim at raising further level 2 and level 3 questions, some of which may have been raised in the earlier part of the session.

Note that although the quiz can help the teacher evaluate student understanding, it also enhances ***quality intellectual work***.

Problem solving and evaluation:The investigation has answered many of the students' level 1 (factual) and level 2 (analysing) and they start raising level 3 (evaluating and synthesizing) questions such as: What are challenges that mango growers might face and how do they relate to the challenges of cultivators of other tropical fruits? What are some of the geographical and weather conditions that are good for growing mangos?

2 – Light bulbs – (tested at college level and in-service teachers)
(a) *Objectives and problem setting*: This lesson can be utilized to develop student understanding of electrical circuits, extending to current flow, voltage, transformation of energy (from electricity to light and heat), and transfer of energy (e.g. from the power station to the home), and other uses of electricity, for example in transportation, energy storage in batteries, etc.

Some introductory hook/questions about the everyday usage of electricity may lead off the lesson. For example, imagine a world without light bulbs? The light-bulbs can all be the same or of many different types: these days they can range from fluorescent to incandescent to LEDS: they can be coloured or clear or frosted glass; it works well with bulbs with a large distribution of sizes.

(b) *The investigative process:* each student receives a light-bulb, and is asked to draw it, and write down two-three inquiry questions - urge them to keep it **RAW** - **R**epresenting **A**nd **W**ondering (Hynes-Berry, 2011); next the students converse in groups of twos and threes, revise their drawings and collaborate on writing down up to three revised questions.

As a whole group, the class discusses some of the group questions: there are varying ways of doing this: groups can write their questions on a "group whiteboard", and the whole-class discussion becomes a "board-meeting"; groups can volunteer their questions; groups can write their questions on the class blackboard; a smart-board with multiple entries from the class groups can be a hi-tech way of proceeding. This format of student feedback in the investigative process is used in "Modeling" (The American Modeling Teachers Association, 2013).

The teacher does not need to ask the questions, and enters the discussion only if he/she wants to guide the discussion to a particular topic, or to stimulate some groups into presenting their questions. An example of guidance would be in wondering how a light bulb fits into an electrical circuit – wondering why most "elements" of a circuit connect at just two points (in and out, or is it out and in? or does it matter?)….

(c) Problem solving and evaluation: One more round of group and/or individual work is very helpful: asking the students to now draw a "scientific diagram" of a light-bulb. At some point one needs to make sure the students know that a scientific diagram generally includes labels of the parts to help clarify the drawing. A final whole group discussion can start from these scientific drawings/diagrams to then connect to their everyday interactions with light bulbs and electrical circuits in general and be guided into the next topic that the teacher wants to cover. Examples might be discussions of why there are so many different types of light bulbs, which are most efficient for producing light, the historical development of civilization's use of electrical power and energy…the students will have great ideas for experiments to test out some of their ideas.

At the end of this lesson, the students can have a much better understanding current flow, voltage, where the energy comes from, why it is important in the modern world, etc. Their next steps might be in building circuits that make the bulbs light up.

3 – Cotton bolls *(tested at K-2, MS, HS, College levels, in-service)*

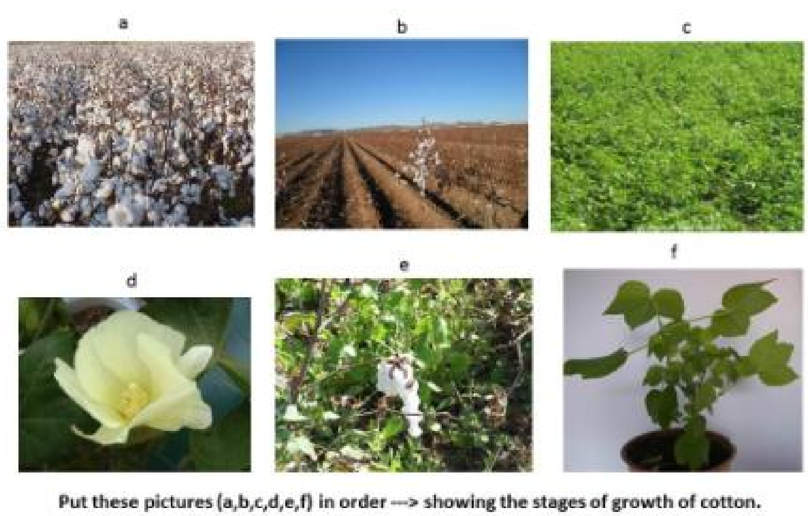

Figure 2. Six pictures of cotton plants at various stages of growth.

(a) *Objectives and problem setting*: The cotton boll lesson can lead to an almost limitless number of possible curriculum areas: an introduction to botany, plant growth and cultivation, mechanization, it also connects with social science - the history of cotton in the United States, slavery, the Civil war and other developments. We found an interesting historical link in Singapore and India (the far east in general) in the restrictive practices in the 19th and 20th century British Empire trade, when all cotton was shipped to England for manufacture; after World War II and the collapse of European colonialism, the trade disappeared, leading to a flourishing manufacturing in Hong Kong, Bangladesh and elsewhere.

(b) *The investigative process:* Each student, (or group of two or three if you have a limited number of cotton bolls) receives a twig of a cotton plant including one cotton boll(The Cotton-man, 2013) and is encouraged to investigate it, draw it, and write down a couple of questions about it: initially, there is a reluctance to pull the boll apart, but soon everyone is separating the 4 bolls from the plant, possibly counting the seeds.

There follows a lively discussion usually focused on the seeds - the numbers in each boll, why are they surrounded by the cotton, how do the plants propagate, etc. We then show the students the 6-part picture (Fig. 2), asking each group to put the 6-parts into chronological order 1 to 6. This procedure can become quite competitive between the groups: since the ordering of one or two of the pictures is not immediately obvious: in one variant, we ask each group to list their order in a column on the blackboard: the ensuing discussion tends to raise many questions about the real-life farming procedures of planting, growing and harvesting the cotton.

(c) Problem solving and evaluation: The last procedure has already entered into the final phase of the lesson, with the students discussing the results of their analyses. Their questions are becoming higher level questions (table I) requiring evaluation and synthesis and developing a network of new connections. There are many directions that the discussions can lead to, and we just mention a few here: the students note how difficult it is to remove the seeds from the boll which becomes a lively history lesson about the invention of the separating machines, the need for slaves in the American south. Another direction can be about the process of making the tee shirts worn by many of the students in the class - where are they made and why? And another can be about the climate and conditions needed for growing cotton; what is the difference between cotton and other fabrics such as wool or synthetic materials. The teacher can be planning the directions he/she might want the students to pursue in follow-up projects, which can be internet assisted reports, confirming some of the discussion topics generated *by the students* in the class..

***4 – Mosquitoes** (tested at MS, in-service, adult levels)*

(a) Objectives and problem setting: This example is focused on animal/insect biology, and developing the students' the abilities to observe and interpret. Since everyone has been "bitten" by mosquito at some time in their life, there is an immediate connection to reality. Just asking what is meant by the two words "mosquito bite" can initiate a strong engaging discussion amongst people of all ages. One does not even need to ask whether a "bite" has to involve teeth?

(b) The investigative process: This begins with the request to draw a mosquito, and write down at least two inquiry (**RAW** - **R**epresenting **A**nd **W**ondering) questions. It is interesting that almost all these "first-drawings" are made very small, as if the student is remembering that the mosquito is small, but they often look more like four-legged creatures – dogs, cats, sheep- each with four legs: one of the most common questions is "how many legs", which gives a chance for one of the smarter students in the class to point out that all "insects" have six legs by definition of "insect". This can be a great lead-in for the teacher in a later class (or right away) when the classification of all species is being introduced. Following the whole class discussion of the questions raised, we pass out photographs of

various mosquitoes, at least one per group; alternatively, we can show a slide of several of the photos, which can include pictures of the eggs and/or pupae and/or larvae. These latter can be included to stimulate deeper questions about the life-cycle of mosquitoes, if that is where the teacher wants to take the class.

The student groups then revise their drawings using the photos to guide them. Either before or after this step, the class can discuss what is a "*scientific* drawing" and then each group can produce a scientific drawing straight from the photos – hence, one can make this a one-step or two-step process – both ways works well, as long as the interest and engagement is maintained. Either way, each group should develop their own set of questions. These questions now tend to be much more interpretive and enquiring at levels 2 and 3 in our question ladder. In fact, it helps to encourage such questions during the drawing process.

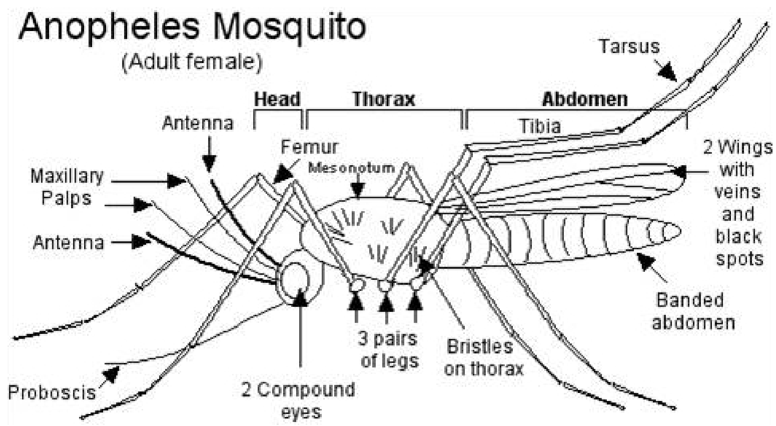

Figure 3. Scientific drawing of a mosquito: adapted from ZOOM School, http://www.enchantedlearning.com/school/index.shtml

c) Problem solving and evaluation: The whole class discussion often starts with questions on the life cycle of mosquitoes: How long do they live? Do they all bite? (species or sex); Why do they need our blood? Is there anywhere in the world without mosquitoes? These are all possible areas for further student investigations and reports. The discussion can be guided using a few outside props and links to the outside: a detailed scientific drawing of a mosquito [Fig. 3]; a wonderful movie of the birth of a mosquito rising from the water (Nuridsany and Perrenou, 1997), ("the birth of evil" – is there a benefit to anyone from a mosquito?); discussion of the role of the mosquito and yellow fever in building the Panama Canal.

Note that examples 1, 2 and 3 use real objects, whereas example 4 is necessarily a "virtual" but very familiar object. Some other examples of "real" or "virtual" objects that can be used at most other grades include: catfish, shoes, rocks, coins, maps, soils, leaves, liquids, soft drinks, tee-shirts, any single or set of vegetables, fruit or flowers, etc. The list is as broad as the teacher's imagination. The break-out parts of the lesson may be differently arranged, but should still follow the SIP and PIP guidelines.

Conclusions

We have explored the power of guiding inquiry in a way that allows individuals to construct their own understanding of the "Big Idea" that is the focus of an inquiry. Students "*read an object*" in a series of steps that lead them to a conceptual understanding of the scientific and other qualities of the object, and its relationship to other ideas, concepts and their own life-events. The process of giving greater ownership of the questions to the learner increases the learner's engagement and results in more efficacious learning as well as a further cycle of inquiry. We discussed the differences between this kind of learning: meeting the standards of quality intellectual work that practicing scientists and adult professionals engage in: and the integration of different concepts into their learning experience, in comparison with school-based "mastery learning" which tends to be forgotten once the short term objectives of a test score are achieved.

Our examples of the "*reading an object*" procedure showed how "reading" simple objects can lead to learning at all levels in all areas of the curriculum. The objects can be simple, familiar or unusual and/or complex. Our process of reading an object has very distinctive guidelines, but is a very open student-sensitive process. Other materials such as pictures, books, the internet, etc., developed from the flow of student questioning and understanding are equally applicable "objects to read".

This approach is very relevant for 21st century classrooms, as it incorporates the 8 essential practices that will underlie future assessments—so that, for the students, we go beyond testing recall of science concepts to be able to investigate the world around them, through the practices of science inquiry.

In short, we have elucidated a practical and effective use of the essential ABCs of learning—a framework that brings the NGSS practice standards to life:

Always **B**e **C**onnecting;
Always **B**e **C**ommunicating;
Always **B**uild **C**onfidence.

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