"Stop I can't Fit Anything More Into My Head: How Students Learn Physics"

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"Baffled Investigators and Educators Disclose…Boy can see with his ears."

"A cross between human beings and plants…Scientists on verge of creating plant people…bizarre creatures could do anything you want."

"Bigfoot found living in Los Angeles, scientists reveal."

Did you ever stop to wonder why the declarative sentences in comic books always ended with exclamation points? Were all those exchanges between Lois Lane and Superman really startling? Were the characters saying them really that thrilled? Of course not. The exclamation points were there to give the story more pizzazz.

The National Enquirer uses a similar gimmick. Whenever it prints a headline trumpeting the discovery of some bizarre, hitherto unheard of phenomenon, instead of ending with an exclamation point, it end (or begins) with a reference to "baffled investigators, "bewildered scientists," or similarly stumped savants. This is a ploy to make their stories seem more credible.

Or is it? What do the editors really want? Do they want a story to appear credible or incredible? It seems that they want it both ways: they want the story to sound as outlandish as possible *and* they want it to have the appearance of authenticity. Therefore, their headlines embody a contradiction: impossibility coupled with verified authority—in short, confirmed nonsense.

As teachers who are constantly learning new ways to reach students, we all have our toolboxes, our hooks, and our exclamation points that help up reach and motivate students. Unlike Marvel Comics or *The National Enquirer*, our audience is, perhaps, more resilient to being duped and our objective of producing a scientifically literate society too important to take casually. I would like to reflect this morning on one area or research in science education that enables us to reach out and to help students create their own conceptual change. The ever-insightful wit of Mark Twain noted, "It's not what you don't know that hurts you. It's what you know that ain't so." A century later, science educators have rediscovered what Twain so cavalierly stated: *Every student approaches learning with a set of assumptions of how the world works*. Sometimes these notions are conscious observations and, at other times, they are unconscious biases that filter, shade, and cast students' perceptions and learning. As in quantum physics, the separation—the distinction—between learner and the "world out there" is blurred and only the interaction of the two is measurable and real. All our knowledge of the world depends on our ability to construct models of it. And as Twain also noted, "You can't depend on your judgment when your imagination is out of focus."

In my astronomy course for non-science majors, I routinely assign question that asks students to determine the number of Big Macs, placed side-by-side that would fit between the Earth and the Sun. The purpose of the exercise was to have students estimate the size of a Big Mac, form a ratio, and then reflect on the result. By the way, did you know that McDonalds has sold more hamburgers (over 100 billion) than there are starts in the Milky Way? We used to call such large numbers astronomical; I guess we should call them *gastronomical*. Although most students obtained reasonable answers, two results stood out: One result was 10^{-13} and the other was 5. A colleague of mine was disturbed by the result of 10^{-13} since it indicated that the student had no common sense about relative sizes. I noticed that that result could be formed if the inverse of the ratio, that is the size of a Big Mac divided by the Earth-Sun distance, were formed. The answer of 5 was far more intriguing. So I sat down with the student and inquired about how he obtained his result. At this point I should state that by the date the homework was due, we had been discussing angular measurement in astronomy and at nighttime observations I repeatedly pointed out how an outstretched fist could be used to estimate the altitude of a star, such as Polaris, above the horizon. This student had applied his newly gained knowledge very well. He estimated the size of a Big Mac to be the size of his fist and then he proceeded to find out how many fists would fit from the horizon to the Sun!

Student learning in science is indeed a very complex process partly because of the abstract nature of many scientific concepts. Physics attempts to describe a maximum of phenomena with a minimum set of variables. We also know that a student is not a *tabula rasa*—a blank slate—when they enter a course. Students bring their own cultural and experiential knowledge to bear on any task and, in general, the more abstract the model of reality, the more they use their own assumptions about how the world works. The matter is further complicated by the fact that understanding of the acceptable models of reality, that is, good scientific understanding, with existing pre-conceptions. In other words, the wheat grows with the weeds and our task as educators is to nurture the wheat and to induce the weeds wither. Herein is where the science of physics teaching merges with the art of teaching.

Ausubel in 1978 was among the first to describe the importance of the knowledge that students held before coming to science classrooms. This experiential knowledge has a profound effect on how what students learn as a result of their science classroom experiences. Meaningful learning as occurs when new information is linked with existing concepts, and integrated into what the learner already understands. A goal of teaching science then is to assist students in making connections between what they learn in science classrooms and what they already know.

Piaget argued that a person expects to understand each new experience in terms of what he/she already knows, that is to assimilate the experience. Or as Nietsche, expressed it "Understanding is being able to express something new in terms of something familiar." When a student is unable to reconcile a new experience to previous ones then some confusion occurs. To reestablish mental balance the student brings meaning to new experiences through accommodation. This process requires a student either to restructure currently held knowledge or to construct entirely new knowledge. In isolation or through group interactions, without the help of a teacher or sometimes through a teacher's instruction, students form their own notions of how things work, how puzzles are solved, how to cope in the world. Sources of students' preconceptions, therefore, can be traced to their experiences, their interactions with peers and others, language, and a curriculum of "truths" that is taught.

A wide range of studies exploring student preconceptions has been made over the past two decades. Among those explorations was work that I conducted in the development of **The Mechanical Universe** *High School Adaptation*. Interviews with high school teachers and students as well as with college students produced a long list of alternate conceptions along with some strategies to overcome them. Here are a few fun examples of alternate conceptions that middle school and high school students have:

- One horsepower is the amount of energy it takes to drag a horse 500 feet in one second.
- Vacuum: A large, empty space where the Pope lives.
- Momentum—what you give a person when they are going away.
- Water is composed of two gins, Oxygin and Hydrogin. Oxygin is pure gin. Hydrogin is gin and water.
- When you smell an odorless gas, it is probably carbon monoxide.
- You can listen to thunder after lightning and tell how close you came to getting hit. If you don't hear it, you got hit, so never mind.
- The tides are a fight between the Earth and moon. All water tends towards the moon, because there is no water in the moon, and nature abhors a vacuum. I forget where the sun joins in this fight.
- When people run around and around in circles we say they are crazy. When planets do it we say they are orbiting.
- The Earth's magnetic field holds you down.

A particularly persistent alternate conception is that in a vacuum there is no gravity. I have found that many students view gravity as being caused by air, and that they believed without air there was no gravity. In addition, some student think gravity acts on falling objects but not on stationary ones. While working with young students one summer at a local library I had them build whirligigs and then they had to describe how the devices fell and why they fell as they observed. At one point I asked what would happen if they dropped one on the Moon and I showed a slide of an astronaut on the Moon. I had brought the slide because I was prepared for them to say that there was no gravity on the Moon. As I expected, many children yelled out that nothing would happen on the Moon because there is no gravity. There no gravity since there is no air, the students thought. So then I asked them why the astronaut on the Moon did not fly off. Their response was "his space suit gives him gravity" and with that answer I was outfoxed again.

A couple more preconceptions:

- Some people can tell what time it is by looking at the sun. But I have never been able to make out the numbers.
- Most books now say our sun is a star. But it still knows how to change back into a sun in the daytime.

One researcher recently reported that 65% of 250 twelve-year-olds has no idea what a star was. Although we are inundated with space travel through *Star Wars* and *Star Trek,* space travel is seen to occur only between planets; stars are insignificant point of light in the background.

In another study students were shown cards depicting familiar situations and asked questions about the scientific concepts represented. Their results showed one group of students confused common meanings of words with their physics meaning; a second group did not think of force unless motion was occurring; and a third group viewed force as a physical quantity possessed by objects in motion which ran out as they stopped. Other studies revealed that students understood law, as in the law of conservation of energy, most frequently as a *legal* term rather than as a description of objects in nature. Conservation was most frequently interpreted in the environmental sense of using sparingly or wisely.

Other researchers have explored students' understanding of vocabulary used in physics-- understanding of words which were part of their everyday vocabulary but have special meanings in physics, such as, speed, velocity, mass and weight. Student comprehension of the physics meanings was found to be weak and this lack of understanding has important implications for teaching physics because confusion occurs when teachers use the physics meaning and students apply their everyday meaning. I once counted the number of vocabulary words that I was expected to learn in my first year Russian course and came up with approximately 1,400. Then I turned to my copy of Halliday and Resnick and counted the terms that any introductory physics student needed to understand. I found 1,700. Granted, students are familiar with many terms but that familiarity with common usage often hinders understanding physical concepts.

The Russian psychologist, Lev Vygotsky recognized early in the 20th century the inevitable interdependence of thought and language, and, therefore, the centrality of teaching-instruction, particularly dialogue, in learning. Knowledge cannot be transmitted simply and directly by an active knower to a passive learner; it must be constructed by the actively learning student from what the learner already knows and with relevant events and objects as are in the environment at the time.

Vygotsky posited that any pedagogy creates learning processes that lead to development and that this sequence results in zones of proximal development (ZPDs). The ZPD as the difference between the actual development level as determined by an individual's problem solving ability and the level of potential development as determined through problem solving under adult guidance or collaboration with more knowledgeable peers. Put simply, the ZPD is the difference between what a learner can do independently and what can be accomplished cognitively with scaffolding from more knowledgeable others.

When we designed C^3P, the Comprehensive Conceptual Curriculum for Physics, in the mid-90s, the importance of language and communication were integral to the curriculum and supporting activities. In C^3P we created a section of "terminology" as a resource in which the everyday usage, physics meaning, and possible confusions were given for key words.

While we worked on development of C^3P, national standards, such as Project 2061, were also being developed and cast into their final form. I was delighted to see that the standards recognized the need for development of habits of the mind for scientific thinking. In C^3P, we have a cohesive set of objectives, appropriately called *Habits of Mind*, with activities to support the development of objective descriptions, to differentiate between fact and opinion, cause and effect, to listen to others and to respect diverse thoughts, and to develop experiments and carry out measurements. The purpose of *Habits of Mind* is to initiate the conversation necessary for the ZPD since central to the curriculum is the conversation students have their peers. By identifying key exploration activities for group word and promoting whiteboard presentations of group findings, we strive to accommodate students ZPD and to progress to critical thinking in physics.

Mark Twain also noted "supposing is good, but finding out is better." As learning in science began to be viewed as an individual student process of concept development a need for a different view of learning and knowing became necessary. Learning has come to be viewed as an individual process carried out in each student's mind as individual knowledge construction and concept development. As this view spread constructivism began to be used in the science education literature to describe and explain learning. Learning in science could best be viewed as knowledge construction with learners having an active role in the process. Student verbalizations of ideas and concepts function as a window onto student conceptualizing, thinking, and concept development. As effective teachers have long realized student dialogue assists in understanding how students are thinking about particular concepts in science or physics.

Howard Gardner, a Harvard psychologist who specializes in cognitive theory, offers us insight into what happens when conceptual change occurs. In order to change someone's conceptual understanding, Gardner writes, one has to produce a shift in that person's perceptions, codes, and the way he or she retains and accesses information. He cites seven levers to change:

1. Reason—the act of logical inspection;
2. Research—the act of study;
3. Resonance—the experience of understanding;
4. Representational redescriptions—visual representations;
5. Resources and rewards;
6. Real world events;
7. Resistance-persistent images to which the student is attached.

Creating conceptual change in students involves engaging the student and reshaping his/her concepts to more acceptable scientific models. Change can only take place when the representational models take new forms. This requires the agent of change, i.e., the teacher, to engage the student in a process of tearing down the existing model and reconstructing one in a new form. This action produces new concepts about how the world works. These efforts are aided by resonance, an emotional experience reinforcing the new model. Resistance, or attachments to the old models inhibit the conceptual change. Understanding the preconceptions—the old models—that students bring into the process aids us greatly in creating the change because it gives us an entry point into their thinking.

In the Buddhist tradition there is a story:

> The Master Nan-in had a visitor—a professor--who came to inquire about Zen, but instead of listening the visitor kept talking about his own ideas. After a while, Nan-in served tea. He poured tea into his visitor's cup until it was full. Then he kept on pouring.
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> Finally, the visitor could not restrain himself. "Don't you see it's full," he said. "You cannot get anymore in." "Just so," replied Nan-in, stopping at last. " And like the cup you are filled with your own idea. How can you expect me to give you Zen unless you offer an empty cup?"

Because science is a consensually agreed upon body of knowledge, students, however, cannot independently discover the rules and definitions of the scientific community. Science is public knowledge that is better described as "carefully checked construction" than as discovery. Learning in science involves individuals as neophytes being initiated into the ways of seeing of the scientific community. Without the presence of a teacher as member of the scientific community, students would have no way of knowing a particular viewpoint was shared with the scientific community.

Learners have to acquire rules to manipulate the symbols of science, a process that is impossible without contact with the community of scientists or their representatives. Concepts learned in science classrooms must be similar to those of the scientific community, because there is little value in students carrying away ideas that are significantly different.

It is difficult to separate student behaviors from teacher behaviors because they often occur simultaneously. Seeing teaching and learning as mutually effecting each other seem obvious to practicing teachers, but to this time research attempted to isolate the two process and study them independently.

Learning something new, or attempting to understand something familiar in greater depth, is not a linear process. In trying to make sense of things we use both our prior experience and the first-hand knowledge gained from new explorations. Initially, our curiosity about a science topic is stirred, as we are stimulated by some intriguing phenomena, such as a rainbow, we've noticed. We poke, probe, inquire about, struggle with, and explore the phenomenon until it becomes less mysterious. As we begin to investigate new ideas we put together bits and pieces of prior explorations that seem to fit our understanding of the phenomena under present investigation. Piece by piece we build up our knowledge and understanding of the phenomenon. Sometimes, when the pieces don't fit together, we must break down old ideas and reconstruct them. We extend our newly gained conceptual understanding through discussions and creative efforts such as validating our theories when we solve problems. The clarity we've gained in understanding a concept gives us the ability to apply this understanding to new situations, new phenomena, and new mysteries. This is a continuous and a very personalized process. We bring to each learning experience our developmental level, our personal story, and our personal style.

That is how students, you, and I learn. It is up to the teacher to facilitate the constructivist learning process. The structure of the learning environment should promote opportunities and events that encourage and support the building of understanding. One model for the process that has been very successful employees the five "E"'s: Engage, Explore, Explain, Elaborate and Evaluate.

Engage: In the Engage stage, students first encounter and identify the instructional task. At this stage they make connections between past and present learning experiences, lay the organizational ground work for the activities ahead and stimulate their involvement in the anticipation of these activities. Asking a question, defining a problem, showing a surprising event and acting out a problematic situation are all ways to engage the students and focus them on the instructional tasks.

Explore: In the Exploration stage, students have the opportunity to get involved directly with the phenomena and materials to explore it. Immersing themselves in these activities, students develop a grounding of experience with the phenomenon. As they work together in teams, students build a base of common experience that assists them in the process of sharing and communicating.

Explain: The third stage, Explain, is the point at which the learner begins to put the abstract experience through which she/he has gone into a communicable form. Language provides motivation for sequencing events into a logical format. Communication occurs between peers, the facilitator, or within the learner himself.

Elaborate: In the fourth stage, Elaborate, students expand on the concepts they have learned, make connections to other related concepts, and apply their understandings to the world around them.

Evaluate: Evaluate, the fifth stage, is an on-going assessment process that allows the teacher to determine if the learner has attained understanding of concepts and knowledge. Evaluation and assessment should occur at all points along the instructional process. Some of the tools that assist in this assessment process are: rubrics (quantified and prioritized outcome expectations) determined hand-in-hand with the lesson design, teacher observation structured by checklists, student interviews, portfolios designed with specific purposes, project and problem-based learning products, and embedded assessments

"Mr. Osborne, may I be excused? My brain is full."

Years ago I wondered how the entire universe of hundreds of billions of galaxies each containing a hundred or so billion stars could have fit into space the size of a cherry pit shortly after the Big Bang. A whole universe of understanding unfolded when I realized that, at that stage in the development of the universe, galaxies and stars did not exist as they do today. Only energy existed ($E=mc^2$) and energy doesn't take up room! Likewise, when learning is kinetic new ideas don't add to pre-existing concepts, instead they replace them.

What helps in making learning kinetic? (1) Promoting interaction among students as they learn. Cooperative learning in a group setting often helps each member achieves higher levels of understanding. (2) Asking open-ended questions that do not assume the "one right answer." Kinetic thinking is often exemplified best when the problems are inherently ill defined and do not have a "right" answer. Open-ended questions also encourage students to think and respond creatively, without fear of giving the "wrong" answer. (3) Allowing sufficient time for students to reflect on the questions asked or problems posed. Kinetic thinking seldom involves snap judgments; therefore, posing questions and allowing adequate time before soliciting responses helps students understand that they are expected to deliberate and to ponder, and that the immediate response is not always the best response. (4) Teaching for transfer. A pre-requisite for kinetic thinking is that ideas should "travel well." Ideas will carry over only if teachers provide opportunities for students to see how a newly acquired skill can apply to other situations and to the student's own experiences.

So how do we know that conceptual change has occurred? Here are a few indicators:

1. Students consciously and responsibly raise questions.
2. Students recognize the limits to our understanding.
3. Students discriminate between observation and inference
4. Students draw inference from observations when concrete answers are not available
5. Students develop metacognition--a self-awareness and intuitive thinking and reasoning abilities.

I began this morning’s talk with the science fantasy of *The National Enquirer*. Perhaps it is appropriate that I end with science fiction. Philip K. Dick, the science fiction author who wrote “Do Androids Dream of Electronic Sheep?” which was the basis for the movie *Bladerunner*, writes that science fiction is "not merely a story set in the future, and it not merely a story featuring high technology… It entails a ‘fictitious world’ that comes out of our world, the one we know: This world must be different from the given one in at least one way... sufficient to give rise to events that could not occur in our society…There must be a coherent idea involved in this dislocation…so that as a result a new society is generated in the author’s mind, transferred to paper, and from paper it occurs as a convulsive shock in the reader’s mind, *the shock of dysrecognition*. In good science fiction, the conceptual dislocation—the new idea, in other words—must ...be intellectually stimulating to the reader…[so] it sets off a chain-reaction of ramification–ideas in the mind of the reader; it so-to-speak unlocks the reader’s mind so that that mind, like the author’s, begins to create.” Likewise, in good science instruction, the shock of abandonment of prior and incorrect preconceptions leads to a chain reaction of new understanding.

Memories and perception are central to *Blade Runner*. Eyes are the main visual motif, while the nature of experience and what it is that makes us human are its resonant themes. In *Blade Runner*, androids have evolved from the robotic to the organic. Instead of machines made of electronic circuits, the androids are genetically engineered and entirely flesh and blood. One android, Roy Batty, becomes more human than the humans seeking him. In the final scene, Roy saves the human Decker, who was hunting him, from his literal fall. Decker is visibly affected by Roy's final words and actions that reflect his compassion, his poetic vision, his "soul:"

"I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched c-beams ... glitter in the dark near Tanhauser Gate. All those moments will be lost in time, like tears in rain.”

Our goal is for students’ preconceptions to be lost in time and our stakes are high. Without the next generation of scientists and a citizenry that can make intelligent and informed decisions about science, our future will be lost.