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INSIDE THIS ISSUE

# *The New Aristotelianism?*

A short time ago one of my faculty colleagues accepted an invitation to visit my Physics 302 class – *Computer Applications in High School Physics* – to see how I work with teacher candidates. My students were conducting an experiment to find out why the rate of acceleration of a dynamics cart going up an inclined plan was not the same as coming down the inclined plan. After watching for a while my colleague remarked that this is the way we ought to teach university physics – students devising experiments, collecting and interpreting data, drawing conclusions, and communicating results. I was asked why this was not always the case, and why some teachers continue to teach by telling. After providing my questioner with some initial thoughts, I continued to reflect on this question. I asked myself, "Why is that traditional science teachers – supposedly well-informed – don't change? Isn't there sufficient evidence of improved student performance as well as philosophical reasons to show that we should teach science as both content and process?" Of course there is. Still, why the resistance? Many reasons have been given, but for one that I thought of as a result of an interesting set of circumstances.

This year, 2009, is the International Year of Astronomy. I have a BS degree in astronomy, I operated a planetarium for many years, and locally I'm a well-known amateur astronomer. As such, I'm frequently asked to give talks about astronomy. Because 2009 is the 400th anniversary of Galileo's first use of the telescope, I have been asked to give quite a few talks this year about his story – especially the 1633 trial. When reviewing some literature in preparation for these talks I came upon a phenomenon that seems in some way to mirror the resistance to change by traditional teachers. It is called Aristotelianism. Aristotelian scientists of Galileo's day rejected Galileo's telescopic evidence without seriously considering it.

Many scientists of his day refused to look through his telescope, and when some others did, they argued that Satan conjured up what they saw. It was these colleagues of Galileo – the Aristotelians – who opposed changes

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suggested in the light of new evidence. The science education reformers of today experience the same sort of resistance to change that Galileo faced, and the parallels are uncanny.

We can see the new Aristotelianism when we encounter colleagues who see no benefit in physics education research, who don't want to look at the evidence when it might change their thinking, who feel they don't need to make changes in established methods of teaching that "worked for me", and who don't want to hear about approaches that might require them to make significant changes to their traditional teaching approaches.

When will the modern holdouts change from the belief that all that is needed to teach physics well is a good knowledge of physics? If that were the case, then, in the main, university-level teachers with Ph.D.s ought to be better teachers than high school physics teachers. My considerable experiences over the years have shown the opposite is more often the case. And consider the fact that students most often decide to become physics majors after taking a high school physics course; many of these chose to leave the physics major after encountering a year of introductory physics at the university level. Perhaps teaching introductory physics informed by physics education research and underpinned with a good philosophical understanding of teaching is needed by those resistant to change.

Maybe the only way to achieve the aim of research-based science teaching at all introductory levels is through a paradigm shift in the way we prepare to teach physics. Perhaps university-level instructors should be required during their first year of teaching introductory physics to study and practice approaches known to be more effective than traditional didactic approaches. Will this change come to fruition in our life times? Just like in Galileo's case, probably not.

Modern reformers must look to promote changes in the teaching of introductory physics as the "old guard" departs to be replaced by the next generation. In order for this reform to be fomented, we in the field of physics teaching must learn to talk substance in an age of style.

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# Scientific epistemology: How scientists know what they know

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*Scientific inquiry is only one epistemological approach to knowledge. The author addresses several ways of knowing in science and contrasts them with other approaches to knowledge in order to better understand how scientists in general, and physicists in particular, come to know things. Attention in this article is focused on the processes of induction and deduction, observation and experimentation, and the development and testing of hypotheses and theories. This chapter takes a physicist's practical approach to epistemology and avoids such statements as "the transcendental deduction of the synthetic a priori" more typical of philosophers. Implications for teaching high school physics are included. This article is one of several chapters produced for the book* Teaching High School Physics*, and is intended for use in high school physics teacher education programs at the university level.*

### *Epistemology*

Epistemology concerns itself with ways of knowing and how we know. The word is derived from the Greek words *epistéme* and *logos* – the former term meaning "knowledge" and that latter term meaning "study of". Hence, the word parsed into English implies the nature, source, and limitations of knowledge. As such, the study of epistemology historically has dealt with the following fundamental questions:

- What is knowledge, and what do we mean when we say that we *know* something?
- What is the source of knowledge, and how do we know if it is *reliable?*
- What is the scope of knowledge, and what are its *limitations?*

Providing answers to these questions has been the focus of attention for a very long time. More than 2,000 years ago Socrates (c. 469 BC–399 BC), Plato (428/427 BC – 348/347 BC), and Aristotle (384-322 BC) wrestled with various answers to these questions, but were never able to resolve them. At best they were able only to provide "partial" answers that were attacked time and again by later philosophers the likes of Descartes (1596 – 1650), Hume (1711 –1776), and Kant (1724 – 1804). Not even these giants of philosophy were able to provide lasting answers to these questions, and, indeed, the discussion continues down to the present day. Even a more recently proposed solution to the definition of knowledge – defining knowledge as justified true belief (see Chisholm, 1982) – has failed in the light of arguments proposed earlier by Gettier (1962).

### *Philosophy and Science*

Philosophy often interacts with science – especially physics – at many points and in countless ways. Scientists are often confronted with the question, "How do you know?" Providing an answer to that question frequently is not easy and often moves such a discussion into the field of scientific epistemology. Addressing this subject matter in a brief chapter is a task of great delicacy because, in order avoid being entirely superficial, one must strongly limit the subject matter that one touches upon and the depth of which it is addressed. Authors such as Galileo, Newton, Bacon, Locke, Hume, Kant, Mach, Hertz, Poincaré, Born, Einstein, Plank, Popper, Kuhn, and many, many others have written tomes in this area of the philosophy of science. The present author has been selective in choosing from among the many topics addressed by these authors on the basis of that which will be most suitable for physics teaching majors, and addressing these topics at a level consistent with their need for understanding. Science teachers need to understand the types of arguments that scientists use in actual practice to sustain the subject matter that they claim as knowledge.

Science is more than a conglomeration of facts, and teaching consists of more than just relating the facts of science. Science is a way of knowing that requires a strong philosophical underpinning (whether consciously sought of unconsciously learned). One cannot assume that students who understand the facts, principles, laws, and theories of science necessarily know its processes and their philosophical underpinning. They cannot be assumed to learn the philosophy of science by osmosis; it should be directly taught. It is hoped that the prospective physics teacher will, as a result of reading this chapter, more fully understand the nature and dilemmas of science. It is expected that this understanding will impact his or her teaching for the better. The author also hopes that this chapter sparks the interest in readers to the extent that they will find their way to reading more broadly in this critically important area.

### *Knowledge versus Faith*

When historians say that they know something, is their type of knowledge the same as that of scientists when they say that they know something? Do sociologists speak with the same surety as scientists? When a theologian makes a proclamation, is the degree of certitude the same as that of a scientist? Frankly, the answer to all these questions is in the negative. Science, sociology, history,

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and religion each have their own ways of knowing and different types of certitude.

One fundamental question with which all scientists ultimately must reckon is how they actually *know* anything. Consider for instance the following statements:

- The Earth is a spheroid.
- The Earth spins daily on its axis.
- The Earth orbits the Sun annually.

Most readers will agree with these assertions, but how many of them actually *know* that the Earth is a spheroid, spins daily upon its axis, and orbits the Sun annually? Do they *know* these statements to be correct, or do they merely have *faith* that they are correct? The fact of the matter is that the vast majority of even physics majors will not know the basis for these statements that took scientists many years to develop. The facts underlying these understandings are by no means clear. Indeed, the philosopher-scientist Aristotle argued so eloquently against the motion of the Earth that his reasoning held sway for nearly two millennia. He argued that if the Earth were spinning we should feel the motion, encounter prevailing easterly winds, see the oceans cast off at the equator, and find that projectiles are left behind when thrown into the air – yet we see none of these! So, on what *basis* do current scientists make the above three claims? How do they *know* the answers; how do they *justify* their beliefs?

If a person claims to *know* something rather than merely have *faith* in something, then that person should be able to provide evidence to support the claim. If there is no support for the claim, then one has mere faith and not knowledge. Anyone who claims to know something should always be ready, willing, and able to answer the question, "How do you know?" Scientists – as should all science teachers – must always be watchful of embracing unjustified beliefs for in doing so they are merely embracing opinion. According to Blaise Pascal, "Opinion is the mistress of error; she cannot make us wise, only content."

### *The Nature of Knowledge*

What then is knowledge? It appears that knowledge is to some extent a *justified belief.* In the not too distant past efforts were made to expand upon this definition by including an additional qualifier as in *justified true belief* Chisholm, 1982). Such a definition stated that we know X if, and only if,

> X is true;
> We believe X; and
> We are justified in believing X.

Let's look at an example by considering the following argument:

- When someone jumps out of an open window, the person falls to the ground.
- We believe that when someone jumps out of an open window, the person falls to the ground.
- We are justified in believing that when someone jumps out of an open window, the person falls to the ground.

The first statement clearly has been the case since windows were invented or one can legitimately make that argument. However, might one not be equally justified in saying that someone who jumps out of an open window will fall to the ground *until next Tuesday at noon after which time people will then fall into the sky?* The inferential process based on experience could support both claims unless one makes a *presumption* about the nature of the world: the laws of nature are forever constant and apply the same way to all matter across both time and space.

This view is known as the Uniformity of Nature Principle, and is one upon which all science and scientists rely. It is based on a long human record of experiences with nature, and is supported even in our observations of outer space that show the same physical principles in operation over the entire universe and throughout the distant past.

### *How We Know in General*

There are several ways of knowing things in general, but not all ways would be considered "scientific." Sociologists, historians, and theologians know things in ways quite different from that of scientists. Sociologist might refer to surveys and draw conclusions from demographic data. Historians might refer to primary sources such as written documents, photographs, and eyewitnesses; theologians might rely on scripture considered inspired or the word of God or on the work of a highly distinguished theologian. Scientists, however, would not make these sorts of claims as no scientist or scientific writing is considered the ultimate authority. All paths to knowledge, however, do apply human *reason* to a greater or lesser extent as a generic way of knowing.

#### *Rationalism*

Adherents of *rationalism* believe that logic is the source of knowledge. *Syllogisms,* one form of logic, can be used to derive knowledge if applied properly. Here we use a form of syllogism known to logicians as "modus ponens" reasoning. (There is an opposite form logical construct not dissimilar to this known as the "modus tollens" that denies a particular conclusion, but it will not be dealt with here.) The modus ponens syllogism takes the following form.

If A, then B;
A;
Therefore, B.

The first step of this logical argument is called the major premise; the second step is the minor premise; the third step is the conclusion. Consider the following argument that illustrates the modus ponens type of logical argument. If humans are cut, they will bleed. I am human. Therefore, when I am cut I will bleed. Sounds reasonable. But what is the problem with the following argument?

- If I can locate the North Star, I can use it to find north at night.
- I can locate the North Star because it is the brightest star in the night sky.
- Therefore, the brightest star in the night sky shows the direction north.

Many people will agree with the conclusion of this statement. If you are skeptical, go out and try this line of reasoning on a number of people. You will be amazed with how many will find the argument and conclusion perfectly acceptable. The problem with this statement, as you may well know, is that the conclusion is completely wrong. The major premise is correct; the minor premise is a broadly held misconception that leads to an incorrect conclusion. The North Star, Polaris, is the 49th brightest star in the night sky. Sirius, the Dog Star, is the brightest star in the night sky. Sirius rises roughly in the southeast and sets in roughly the southwest for observers in the mid northern latitudes where the North Star is plainly visible about half way up in the northern sky. Sirius is likely to "point" southeast or southwest near its rising and setting respectively, and south only when it is highest in the sky. Scientists tend to avoid the syllogistic approach to knowledge, as it is "empty". The conclusion cannot state more than what has been noted in the premises, and thus only makes explicit what has been stated previously.

Reason alone, without the support of evidence, is quite limited and subject to error. For example, consider the claim by Aristotle that heavier objects fall faster than lighter objects. This makes perfect sense in light of natural human reason. If a larger force is applied to an object, it accelerates at a higher rate. Now, if the earth is pulling on one object more than another, doesn't it make logical sense that the heavier object should fall faster? But despite human reason, experimental evidence shows that this is wrong. Barring friction, all objects accelerate at the same rate independent of their weight. If Aristotle had only known about Newton's second law, he would have understood that greater mass requires greater force to accelerate it thus canceling the "advantage" of weight over mass. Another example of the failure of reason can be exhibited in responding to the question, "What is the weight of smoke?" One might weigh an object before burning it and then measure the weight of the ashes. The difference between the two is the weight of the smoke. The process fails because it does not take into account the addition of oxygen from the air when it enters into the burning process.

We must keep in mind that one's outlook as well as lack of understanding can sway reason. As anyone who has examined the religious and political arenas will be aware, we tend to believe what we want to believe, and take facts as opinions if we do not agree, and opinions as facts if we do agree. We sometimes gain false impressions when we pre-judge someone or something on the basis of prior impressions. With all these critiques of pure reason, how can anyone actually ever know anything using the approach of rationalism alone?

### Reliabilism

Adherents of *reliabilism* say that they are justified in knowing something only if that something is arrived at using a reliable cognitive process that extends beyond mere human reason. Less subjective than human reason and not subject to self-deception or human bias is *artificial inference* such as the rules of mathematics or Boolean logic. These are ideal approaches for deriving knowledge. Structured logic is the *sine qua non* of reliabilists. Consider for instance, the following knowledge derived from the axiomatic proofs of mathematics. From the relationship $4x + 2 = 10$ one can follow the rules of algebra to reliably conclude that $x = 2$. No question about it. But what can we conclude from the following manipulation where $x$ is a variable and $c$ a constant?

$$x = c$$

Now, multiply each side by $x$.

$$x^2 = cx$$

Next, subtract $c^2$ from each side.

$$x^2 - c^2 = cx - c^2$$

Factor.

$$(x + c)(x - c) = c(x - c)$$

Cancel the common term $(x - c)$.

$$x + c = c$$

Substitute $c$ for $x$ and combine.

$$2c = c$$

Cancel the common term $c$.

$$2 = 1$$

Now, does 2 really equal 1? Of course not. But why not? Clearly, we have arrived at a false conclusion because we have violated one of the rules of algebra. Can you tell which one? The point is that if a person is using artificial inference to derive knowledge, one must be exceedingly careful not to broach any of the rules of mathematics and logic – assuming that all are actually known.

### Coherentism

Adherents of *coherentism* believe that knowledge is secure when its ideas support one another to form a logical construct, much like bricks and mortar of a building supporting one another to form an edifice. Knowledge is certain only when it coheres with similar information. To this means of knowing, *universal consent* can prove to be fruitful. According to the coherentist viewpoint, because "everyone" believes something that it must be so.

No one in their right mind would dispute the statements that Indiana is located between Ohio and Illinois, and that the Eiffel Tower is located in Paris. Many there are who have traveled to Indiana and Paris and know from personal experience the locations of the state and the tower. Besides, there are books and maps and internet references that all say the same thing. Everyone and everything, it seems, agrees with these statements. But be careful. Just because "everyone" believes something, doesn't necessarily make it so. It was once believed by nearly everyone that diseases resulted from humans having displeasured the gods, that the Earth was flat, and that the Earth stood unmoving at the center of the universe.

Coherentism lends itself to yet another way of knowing that can be similarly flawed, that of *perfect credibility.* To the medieval mind it was only reasonable that the Earth was at the center of the universe, the lowest point possible under the heavens. To medieval thinkers humanity was at the center of the universe not because of our noble status as the pinnacle of creation, but because we were so very despicable with our fallen nature. Closer to the center of the universe still was that place at the very center of the Earth that was reserved for the most despicable of all – hell. Those not so terribly bad were relegated to the underworld or Hades upon death, but not hell. This is the reason why the medieval viewpoint envisioned heaven as "up" and hell as "down." Man's position near or at the center of the universe was not pride of place; rather, it was a matter of making perfect sense in man's relationship with the deities. This belief was perfectly credible. Interpreting things in any other way would have made no sense given the then prevailing theological understanding. Still, such conclusions were flawed. Remember, all Aristotle's evidence and argumentation at one time pointed to the fact that the Earth was stationary, but today we know that it spins daily upon it axis and revolves annually around the Sun which is just one of billions of stars located in a typical galaxy, one of billions seemingly scattered almost entirely at random around a universe that has no evident center.

*Credible authority* is another way of knowing based on coherentism, and it is the way that almost everyone has come to "know" what they claim know about the universe. It is this approach that is often used in schools to teach children. The teacher is the authority figure; the children are empty vessels to be filled with "knowledge". While this viewpoint is quite wrong, it does have its uses – and also its limitations. Let's look at the following questions. What is your name? How do you know? Is Labor Day a legal holiday in the USA? How do you know? You know your name because those entitled to name you at birth, your parents, did so. They are credible authorities as only parents have a right to name their children. We know that Labor Day is a national holiday because the United States Congress declared by law that it should be so in 1894. By their legal authority, parents and Congress have performed an act by the very power vested in them. Relying entirely on this approach to knowing can be problematic in many situations as not all authorities are credible. For instance, many religious sects claiming to possess the "truth" preach contradictory beliefs; they can't all be correct. Psychics might intentionally make false claims in order to influence the direction of lives. Financial consultants might seek to mislead clients in an effort to achieve financial gain.

There are several unresolved problems associated with coherentism. When ideas or beliefs conflict, it is not possible to tell which one is to be accepted. How do we distinguish a correct idea from an incorrect idea when incorrect ideas sometimes are consistent with what we already know, or a new idea conflicts with what we "know" to be correct? How do we distinguish a better or more important idea from one less so? What role does bias play a role in our ability to distinguish correctly? Coherentism, it appears, is unable to provide meaningful answers to these questions.

### *Empiricism*

Adherents of classical *empiricism* (a type of empiricism perhaps best suited to teaching high school physics) believe that logic, connected to verification though observation or experimentation, leads to knowledge. The empirical approach to knowledge consists of reason constrained by physical evidence. For example, reason in conjunction with observation helps scientists know that the Earth is spheroidal. Careful observers will note that the North Star descends below the northern horizon for travelers crossing from north to south of the equator at any longitude, that the masts of ships disappear long after the hull when ships travel over the horizon in any direction, circumnavigation of the globe being possible in any direction, and the shadow of the Earth on the moon during a lunar eclipse at any time of night are all pieces of evidence that one can logically use to conclude that the Earth is roughly spherical. Observation in conjunction with reason will lead to no other conclusion.

In its simplest form, one might know something through *personal experience.* If one's hand is burned by a hot piece of metal, one knows it and has the evidence to prove it. One's hand might be red and painful as with a first degree burn, or there might be blisters with excruciating pain as with a second degree burn, or there might even be charred flesh with an acrid smell as in a third degree burn. One's belief is substantiated with evidence; hence, one can support a belief with evidence. One's belief in a burned hand is not merely a matter of faith; one actually possesses knowledge based on reason sustained by ample evidence. One must be careful, however, of assuming that personal experience is the final arbiter of whether or not an experience provides incontrovertible evidence. Some concrete experiences can be interpreted or viewed in different ways. The failure of eyewitnesses to provide identical interpretations is a good example of this. In the case of a robbery, the person who has a gun shoved into his or her face might remember things about the perpetrator of the crime quite differently from someone who witnessed the act from a hidden location. One's perspective can, indeed, influence what one sees or remembers, or how one interprets evidence. People don't always draw the same conclusion based on the same evidence either. In the case of the traditional "boy who called wolf" story, two conclusions can be drawn – either don't lie, or don't tell the same lie more than once!

Improvements in technology can lead to increased precision in observations. Refined observations can then lead to overturning knowledge based on reason and new observations. The history of science is littered with evidence-based models now discarded that were once thought to constitute knowledge. A review of the history of scientific models – the solar system, evolution, the atom, the nature and origin of the universe, the nature and cause of gravitation, predator-prey relationships, genetics, heat and energy – all point to the fact that scientists spend a great deal of time building, testing, comparing and revising models in light of new evidence.

As history shows, even scientific knowledge is tentative. This is so for more than one reason: (1) scientists presume the Uniformity of Nature principle and to the extent that this presumption is wrong, our conclusions based upon it are similarly wrong; and (2) what is accepted at any one point in time by the converged opinion of institutional science is what constitutes established scientific knowledge. Borrowing a page from the book of coherentism, when all the indicators suggest that something is correct, it is assumed to be so until new empirical evidence overrules it. Scientists therefore do not claim to possess "truth" as such because this would constitute something that is known now and forever to be correct, and totally consistent with reality. To make a claim of possessing "truth" would be worse than presumptuous.

This is not to say that scientific knowledge is "weak". The vast majority of what we teach in high school science – especially physics – is not likely to change. Quite the contrary. Our understanding of momentum, energy, optics, electricity, magnetism, and such, is extremely well supported and there is no reason to believe that it ever should change. It is for this reason that scientists say they their knowledge is tentative, while at the same time durable.

### *Induction, Deduction, and Abduction*

*Induction* and *deduction* are at the heart of empiricism. In the process of induction, one generalizes from a set of specific cases; in the process of deduction, one generates specifics from a general rule. Induction can be thought of as a search for generality; deduction can be thought of as a search for specificity. A very simple example will suffice to explain the concepts of induction and deduction.

Suppose a person goes to a roadside fruit stand wanting to buy sweet apples. The fruit stand owner offers up some slices of apples as samples. Taking a bit of one sample our shopper finds that it is sour. He examines the apple and sees that it is hard and green. He then takes another sample and finds that it too is hard, green, and sour. Before picking a third sample our shopper observes that all the apples are hard and green. He departs having decided not to buy any apples from this fruit stand concluding they are all sour.

Granted, two samples is a very minimal basis for performing induction, but it suffices for this example. If one were to examine the thought process that was used by our would-be buyer, one would determine that this is how he reasoned:

All hard and green apples are sour;
these apples are all hard and green;
therefore, these apples are all sour.

We have seen this form of reasoning before and recognize it as a modus ponens form of syllogism. Our shopper has performed an inductive process that relied on specific cases of evidence to generate a general rule. Note then the next lines of the shopper's reasoning:

Because all of the apples are sour,
I do not want to purchase any of these apples.

When the shopper decides to depart the fruit stand without purchasing any apples he does so on the basis of deduction. Using the conclusion established via induction, he made a decision via deduction to leave without purchasing any apples.

Scientists rarely use the syllogistic process when they deal with the subject matter of science because they are not interested in drawing "empty conclusions" about material objects. For instance, "All light travels in straight lines; we have light; therefore, what we have is traveling in straight lines" contributes nothing to scientific knowledge or understanding. To justify the claim that light travels in straight lines we must make observations that lead observers to this conclusion. Data related to the phenomenon must be accounted for in terms of this principle.

*Abduction* is at the heart of generating explanations in science. It is the process of creating hypotheses. The formulation of hypotheses – constructs designed to provide predictions and explanations – begins with examination of available evidence and devising an explanation for it. Abduction sometimes relies upon analogies with other situations. In the previous example, one might conclude from knowledge that sugar gives the taste of sweetness to those things that contain it, that natural sugars are absent in hard green apples. This would explain the lack of sweetness in the apples sampled at the fruit stand. The statement that hard green apples are sour because they lack natural sugars present in sweet apples is a hypothesis derived by abduction. They hypothesis serves to explain why the samples of hard green apples all tasted sour.

Some authors have falsely claimed that hypotheses are generated from the processes of induction. This is incorrect. Inductive processes can only provide general statements and, as such, cannot explain anything. The relationships between induction, deduction, and abduction are shown in Table 1.

| **Intellectual processes and their connections to science** |
|---|
| *Induction* is most closely related to the generation of principles and laws in science. Principles identify general relationships between variables such as "When water is heated in an open container, it evaporates." Laws identify specific relationship between certain observable quantities such as "The period of a pendulum is proportional to the |

| |
|---|
| square root of its length." Principles and laws are descriptive, and almost without exception can be stated in a single formulation, and have no explanatory power. Laws and principles are established on the basis of direct evidence. Principles and laws are resilient because they are based directly on observational evidence and not upon a hypothesis or theory. Even when a hypothesis or theory that explains them is proven false (e.g., Wien's displacement law with the failings of classical electrodynamics, Balmer's spectral law in the light of the failed Bohr model), principles and laws survive the demise of the hypothesis or theory. |
| *Deduction* is most closely related to the generation of predictions in science – the process of using principles, laws, hypotheses, or theories to predict some observational quantity under certain specified conditions. |
| *Abduction* is most closely related to the generation of hypotheses in science – tentative explanations that almost always consist of system of several conceptual statements. A hypothesis, because it often deals with unobservable elements, often cannot be directly tested via experiment. An example of this would be electron theory that notes that electrons are carriers of an elementary charge, the assumption of which served as the basis of the Millikan oil-drop experiment. Sometimes, the sole basis for accepting hypotheses is their ability to explain laws, make predictions, and provide explanations. For instance, Newton's formulation of gravity was accepted on the basis that it was able to account for Kepler's three laws of planetary motion. So it was with Copernican theory, the corpuscular theory of light, atomic theory of the Periodic Table, and the kinetic theory of gases. Bohr's model for the atom and Einstein's special and general theories were similarly accepted on the basis of their ability to make accurate predictions and provide explanations. |

Table 1. *Connections between intellectual processes and scientific nomenclature.*

### *Induction in Science*

Central to the inductive process in science is observation. *Observation* is key to many sciences. Biologists, for instance, learn about the lives and behaviors of animals by making observations. They accumulate a large amount of data about, say, gorillas, and how they interact under certain conditions. Geologists likewise collect data by studying minerals and maps, examining rock formations, and reviewing earthquake data from their seismographs. Meteorologists similarly collect data about the weather such as temperature, barometric pressure, relative humidity, wind speed and direction, and so forth. Scientists do not stop there, however. Raw data per se are of little use, and no scientific journal will publish long lists of data. Scientists are not merely "cameras" expected to record data (Bronowski, 1965). Rather, it is only when they synthesize conclusions based on observations that they are doing the work of scientists. (See sidebar story 1.)

SIDEBAR STORY 1

#### Induction and the Genius of Isaac Newton

Isaac Newton (1643-1727, Julian calendar) used induction as the basis of what is known today as his theory of gravitation. Now, the story of Newton sitting under an apple tree seeing an apple fall and thinking about the form of gravitation is probably apocryphal. Nonetheless, it could have occurred to Newton that the fall of an apple is not unlike the fall of the Moon as it orbits the Earth. It was the fact that he was able to understand the relationship between the Moon's and the apple's acceleration that constitutes the genius of Isaac Newton. Couched in modern SI terms, and *using the simplifying assumption of circular motion,* this is what Newton did. First, he realized that the acceleration of, say, an apple near the surface of the Earth was

$$a_{\oplus} = 9.8\frac{m}{s^2}$$

He then calculated the centripetal acceleration of the Moon in its orbit around the Earth by using an equation first provided by the Dutch scientists of his day:

$$a_{\supset} = \frac{v^2}{r}$$

The speed of the Moon's motion was easily derived from the relationship into which he put the proper values for the orbital radius of the Moon and its orbital period (both known with a relatively high degree of precision in Newton's day)

$$v = \frac{d}{t} = \frac{\text{circumference}}{\text{period}} = \frac{2\pi r}{P} = \frac{2\pi(3.84x10^8 m)}{2{,}360{,}000s} = 1020 m/s$$

Using the equation for centripetal acceleration, he then came up with the value of the Moon's acceleration

$$a_{\supset} = \frac{(1020 m/s)^2}{384{,}000{,}000 m} = 0.00271 m/s^2$$

He then compared the acceleration of objects near the Earth's surface with that of the Moon in orbit and found

$$\frac{a_{\oplus}}{a_{\supset}} = \frac{9.8 m/s^2}{0.00271 m/s^2} = 3600$$

He then realized that 3600 could well represent the ratio of the Moon's orbital radius to the Earth radius squared.

$$\frac{a_{\oplus}}{a_{\supset}} = 60^2 = \left(\frac{r_{\supset}}{r_{\oplus}}\right)^2$$

From this formulation, Newton surmised that the acceleration of an object (be it the Moon or an apple) is inversely proportional to its distance from the center of the Earth squared (and perhaps where he first realized that the Earth acts as though all its mass is concentrated in a point at its center). That is,

$$a \propto \frac{1}{r^2}$$

Given the fact that $F = ma$, Newton concluded that the force required to hold the Moon in its orbit around the Earth was also dependent upon the mass of the moon, $m$. That is,

$$F \propto \frac{m}{r^2}$$

Because gravity is responsible for the perceived weight of objects, and would likely be proportional to the mass of the Earth, $M$, as well as the moon, Newton further hypothesized that,

$$F \propto \frac{Mm}{r^2}$$

Inserting the proportionality constant, $k$, gave Newton his final formulation for the force due to gravity.

$$F = k\frac{Mm}{r^2}$$

It wasn't until the 1797-1798 experimental work of Henry Cavendish (1731-1810) that the value of $k$ was determined. Once he did so, the $k$ was replaced with a $G$ giving us the now familiar expression

$$F = \frac{GMm}{r^2}$$

So, it should be evident from this work of induction that Newton's act of creative genius was in the fact that he was able to use observational evidence to formulate a relationship to determine the nature of the central force required to keep objects in orbital motion. Edmund Halley (1646-1742) used Newton's formulation of gravity and observations of an earlier bright comet to predict its return. That comet, now named Halley's Comet, returned as predicted in the year 1758. Later Urbain Leverrier (1811-1877) and John Couch Adams (1819-1892) independently used Newton's formulation of gravity to analyze the irregular motions of the planet Uranus, and predict the location of a hitherto unknown planet – Neptune – discovered in 1846. These cases used Newton's formulation of the force due to gravity to make predictions and, as such, are examples of deduction.

Principles and laws are inferences that result from the generalization of different types of data. Principles are general relationships between observable properties. As the day progresses and the land warms, warm air rises over the land and is replaced by cool breezes that blow from the sea to the land. We see that when air warms, it expands and thereby gaining buoyancy. We see that living organisms require energy in order to survive. We see the conservation of energy in its many forms. We see that objects fall to the ground when left unsupported. We conclude that light travels in straight lines. These are all principles of science. The empirical laws of science are more abstract than general principles in the sense that they typically incorporate mathematics in their expressions. Examples of laws in physics are numerous, and would include such things as the law of levers, the law of pulleys, the law of mechanical advantage, the laws of kinematics and dynamics, the laws of thermal expansion, the conservation laws in mass, energy, and charge, Newton's second law of motion, Ohm's law, the laws for series and parallel circuits, the thin lens formula, Snell's law, and the laws of relating to heat and change of state, Boyle's law and the ideal gas law. All relate mathematic variables in precise ways. These are all "simple" examples of induction based on experimentation.

There are many examples of more sophisticated forms of induction where scientists have linked areas of physics to arrive at a new and more meaningful understanding. Isaac Newton did this by linking motion to force; Michael Faraday did this by connecting electricity with magnetism; James Clerk Maxwell did this by unifying electromagnetism with light; Albert Einstein did this by interfacing time with space, mass with energy, and force with geometry. It was the ability of these scientists to make sense of information that gave value to their ideas, and allow us to call them genius.

*Observation* and *experimentation* are central to the inductive process. But physical laws, primarily those of classical physics, were initially derived with the use of experimentation. No amount of observation would have allowed a casual observer to discover any of the laws mentioned above. These are empirical relationships based controlled experimentation.

### *Deduction in Science*

One of the main goals of scientists and engineers is to perform deductive processes. Scientists use inductive processes to formulate principles, laws, hypotheses, and theories from which they can then deduce predictions. For example, applications of various empirical laws such as $\boldsymbol{\Sigma F = ma}$, $\Delta V = IR$, and $\Delta L = \alpha L_o \Delta T$ can be used to predict future situations under certain conditions. One can, given the force on and mass of a vehicle, predict its acceleration.

Applying a voltage difference across an electrical network with a known resistance, one can predict the consequent current. Heating a particular rod of known length and composition by a certain amount, one can determine in advance what the change in length will be. Almost every piece of technology that we have today has been designed using the deductive process. This is true on a vast scale, from nanotechnology to an aircraft carrier.

Astronomers are observationalists par excellence and are very good at applying what they know from Earth-based studies to deduce knowledge about celestial objects. They cannot bring planets, comets, stars, nebulae, or galaxies into the laboratory for experimentation. They do, however, apply principles, laws, hypotheses, and theories to their observations in order to learn about celestial objects. For instance, Edwin Hubble was able to use the distances and motions of remote galaxies to determine the age of the cosmos. Using variants of the Hertzsprung-Russell diagram, astronomers were able to deduce how it is that stars are born, live out their lives, and die even though the process can take millions or billions of years. Using the laws of thermodynamics and nuclear theory, astronomers have been able to discover how it is that stars operate. Earlier than any of these examples, astronomers made use of Newton's universal law of gravitation and observations of an orbiting moon to deduce the mass of Jupiter. (See sidebar story 2.)

SIDEBAR STORY 2

### Deduction of the Mass of Jupiter

A generation before Newton, Johannes Kepler (1571-1630) enunciated three planetary laws of motion based upon observations of the planet Mars made earlier by Tycho Brahe (1546-1601). Kepler stated these laws roughly as follows:

1. Planets move in elliptical orbits around the Sun with the Sun located at one of the foci.
2. The radius arm between a planet and the Sun sweeps out equal areas in equal time intervals.
3. The period of a planet expressed in years squared equals the semi-major axis of the orbit expressed in astronomical units (equal roughly to the average Earth-Sun distance) cubed. That is,

$$P^2 = r^3$$

If the units other than years and astronomical units are used (e.g., SI units), then the form of the equation would be expressed as

$$P^2 = (\text{constant})r^3$$

where the value and units of the constant would depend upon the units employed in the equation's other variables. At this point Newton, with his second law, the definition of centripetal acceleration, and his new formulation of gravity, was able to write

$$F = ma = \frac{mv^2}{r} = k\frac{Mm}{r^2}$$

Substituting for $v = (2\pi r/P)$ and simplifying the two rightmost components of this equation, Newton arrived at the following relationship

$$P^2 = \frac{4\pi^2 r^3}{kM} = (\text{constant})r^3$$

which is Kepler's third or harmonic law! Newton's formulation of the law of gravity therefore was able to explain the origin of the harmonic law– it's due to the fact that gravity is an inverse-squared force. Newton's hypothesis then, with this firm underpinning, was on its way to becoming theory.

It should be noted, too, that Newton's more detailed analysis of the central force problem resulted in a prediction of elliptical motion. That is, when gravitational force is assumed to drop off with in inverse-square of the distance, then elliptical motion results. This is precisely what Kepler observed. Newton's law of gravitation, $F = Gm_1m_2/r^2$, was also used to explain Kepler's law of equal areas. These derivations are beyond the scope of this book, but provide additional bases that led to the universal acceptance of his formulation of the law of gravitational force.

Note that the above formulation of Kepler's harmonic law is for the simple case that assumes purely circular motion. In reality, the solar system's moons and planets move with barycentric motion. That is, the sun and planets, the planets and the moons orbit the centers of mass in they systems. Taking this consideration into account (*and retaining our assumption of circular motion for simplicity*), Newton was able to derive a more precise form of the Harmonic law

$$(M + m)P^2 = \frac{4\pi^2(R + r)^3}{k}$$

This relationship later was employed to measure the masses of various solar system bodies using solar mass units for mass and astronomical units for distance of measure long before the space age. For instance, if the mass of a moon of Jupiter, *m,* is taken to be very small in relation to the mass of Jupiter, *M,* and the distance of Jupiter from its barycenter (*R*) very small in relation to the distance of the moon from its barycenter (*r*), then we can simplify the above relationship

$$MP^2 = \frac{4\pi^2 r^3}{k} \quad \text{(assuming } m << M \text{ and } R << r\text{)}$$

In more modern form, the relationship can be written at follows:

$$M = \frac{4\pi^2 r^3}{GP^2} \quad (\text{assuming } m << M \text{ and } R << r)$$

A series of observations of the Jovian moon Ganymede shows that it has an orbital period of 618,100*s* (7.154 days) and a mean orbital radius of 1,070,000,000*m.* Putting these data into the equation with the proper value and units for *G* results in a mass for Jupiter of 1.89 x $10^{27}$*kg.* Hence, the mass of Jupiter has been deduced from theoretical considerations integrated with observations. Fly-by missions to the planet later confirmed this deduction.

Deduction takes different forms, from the mundane to the complex. These extremes in this article are typified by using a formula to predict the outcome of a particular situation, to using observational evidence and a hypotheses or theory to determine the mass of Jupiter. Deductions – and some will say predictions – are characterized by two logical conditions (Nagel, 1961): (1) the premises must contain at least one universal law, hypothesis, or theory whose inclusion is essential for the deduction, and (2) the premises also must contain a suitable number of initial conditions. These latter conditions constitute an "if – then" combination. For instance, if the voltage difference is $\Delta V$ and the current $I$ in an electrical circuit, then the effective resistance must be $\Delta V/I$.

Observations inform us about the past and present, and reason in the form of a logical deduction can be used to predict the future. The law of levers can be used to predetermine combinations of force and distance that will balance one another. In a more sophisticated sense, a knowledge of Newton's second law, $\boldsymbol{\Sigma F} = m\boldsymbol{a}$, can be used to predict the first and third laws as special cases of the more general form of the second law.

The knowledge of the past and present is known with relative certainty compared to knowledge of the future. Still, if we are willing to accept the assumptions about the nature of the universe (uniformity, causality, etc.), then we must conclude that the predictive methods of science are tenable, and we can in a sense foresee and foretell the future. The worth of any such prediction can only be measured in relation to its verification. If a prediction is verified, this lends credence to the universal law, hypothesis, or theory upon which the prediction was made.

### *The Hypothetico-deductive Method*

Closely linked with the scientists' use of induction and deduction is the process of hypothetico-deduction. This is a simple and effective method of advancing the frontiers of science and, in many cases, increasing our understanding of nature. The basic gist behind this method is the formulation and testing of hypotheses. That is, hypotheses can be generated from simple observations. Hypotheses, tentative explanations, then result in predictions that necessarily must follow from a hypothesis, and if corroborated with empirical evidence, sustained. As Popper (1962) noted, scientific hypotheses are conjectures that have a potential for being refuted. If the evidence disconfirms the hypothesis, the hypothesis is either rejected or modified. Well-sustained hypotheses become theories, the value of which can be judged only in relation to their ability to make further predictions and explain more observations in order to account for diverse physical phenomena. Hypotheses are well thought out explanations that incorporate evidence, not mere guesses as is all too often implied by the use of this term in the vernacular. Also to be avoided is the phrase "educated guess" which a hypothesis clearly is not. Neither are hypotheses to be confused with predictions, as is too often the case in even the science classroom.

To help clarify the meaning of a hypothesis and relate it to predictions, consider the following very simple example. A physics student who has just completed a study of energy looks at the following kinematics relationship and thinks she "sees" a conservation principle contained within it.

$$v^2 - v_0^2 = 2ad$$

Working under the hypothesis that this kinematic law derived from observation has the form it does because it incorporates conservation of energy, the following prediction is made: If kinematic laws hold because they are based on the conservation of energy, then kinematic laws should be derivable from the statement W=ΔE, the work-energy theorem. The student sets to work.

$$\Delta E = W$$

$$\frac{1}{2}mv^2 - \frac{1}{2}mv_0^2 = Fd = mad$$

and, after multiplying both sides by $\frac{2}{m}$, she gets

$$v^2 - v_0^2 = 2ad$$

So, this supports the basic assertion that kinematic laws hold because they are based on the conservation of energy. But does this derivation "prove" anything? Not necessarily. The outcome is merely consistent with the assumed basis for this particular kinematic relationship. Now, if conservation of energy is the basis of kinematic relationships (assumed free from resistance), then conservation of energy should also be visible in all other kinematic laws as well. We should be able to derive kinematic relationships from the work-energy theorem and visa versa. Consider the following derivation:

$$d = d_0 + v_0 t + \frac{1}{2}at^2$$

$$(d - d_0) = v_0 t + \frac{1}{2}at^2$$

$$F(d - d_0) = mav_0 t + \frac{1}{2}m(at)^2$$

and given that $v - v_0 = at$

$$W = mav_0 t + \frac{1}{2}m(v - v_0)^2$$

$$W = mav_0 t + \frac{1}{2}m(v^2 - 2vv_0 + v_0^2)$$

$$W = mav_0 t + \frac{1}{2}mv^2 - mvv_0 + \frac{1}{2}mv_0^2$$

$$W = mav_0 t + \frac{1}{2}mv^2 - m(v_0 + at)v_0 + \frac{1}{2}mv_0^2$$

$$W = \frac{1}{2}mv^2 - mv_0^2 + \frac{1}{2}mv_0^2$$

$$W = \frac{1}{2}mv^2 - \frac{1}{2}mv_0^2$$

$$W = \Delta E$$

The working hypothesis that kinematic relationships hold due to conservation of energy appears to be borne out. The fact of the matter is that even the definitions of acceleration and average velocity shown in the relationships $v = v_0 + at$ and $d - d_0 = \overline{v}(t - t_0)$ also can be derived from the work-energy theorem and visa versa, but these derivations are left for the student. (See the results of the anticipated student work at the end of this document.)

The insight that conservation of energy is responsible for the form of kinematic equations is crucial for their appropriate application. They are valid only so long as energy is conserved. To the extent that energy is not conserved in a particular situation (e.g, friction), the kinematic equations are invalid. While this is a very simplistic example of the hypothetico-deductive method, it suffices to show how the process works and to explain some of the understanding that can be derived from such an approach.

Perhaps a better example of the formulation of a hypothesis in physics would be in developing an explanation of the source of the buoyant force ($F_B$) experienced by objects immersed in a fluid of density $\rho$. Noting that law that states that pressure ($p$) increases with depth ($p = \rho gd$), one can calculate the differences in the forces due to a fluid on the top and bottom surfaces of an imaginary cube of dimension $A$ ($F = pA$) at different depths. This difference in these two forces amounts to the buoyant force experienced, and can even predict the value of the buoyant force from the relationship so derived. That is, $F_B = \rho Vg$. (See sidebar story 5 in Wenning (2005) for a detailed explanation.)

### *Empiricism in Science*

Scientific knowledge is belief based on reason and empirical evidence; while it is tentative, it is still quite durable and, in most cases of established science treated in high school, unlikely to change. A scientific understanding of nature is an understanding that has been tested against the empirical evidence that nature provides, and not found wanting; a scientific law, hypothesis, and theory can be tested against empirical evidence with the use of predictions.

Nature itself is the final arbiter in any disagreement between principles, laws, hypotheses, and theories developed by scientists. Prior to the scientific revolution, scientific knowledge was based upon ancient authorities, especially Aristotle. Religious dogmas, particularly those proposed by Thomas Aquinas (1225-1274 AD), also played a pivotal role in the establishment of knowledge that intruded upon the 1633 trial of Galileo. After the scientific revolution, facts, principles, laws, hypotheses, and theories were subject to objective judgment in the light of empirical evidence.

Galileo's telescopic observations during the early part of the 17th century showed Ptolemy's model of the solar system to be wrong, but did not confirm that the model proposed by Copernicus was correct. In fact, later observations showed that even Copernicus was incorrect. Neither did Galileo's observations eliminate a competing model of the solar system, the Tychonic system, which quite admirably accounted for Galileo's observations. In this model, the Earth was at the center of the known universe and the Sun orbited the Earth daily. The planets in turn orbited the Sun. Galileo's observations were not inconsistent with this alternative model. It wasn't until adequate observations were made that it became clear that the Keplerian model of the solar system that dispensed with the perfect circular motion of Copernicus and replace it with elliptical motion, was correct. Incontrovertible empirical evidence of the Earth's motion wasn't obtained until Bradley observed the aberration of starlight (1729), Bessel discovered the parallax of the double star 61 Cygni (1838), and later empirical evidence in the mid to late 19th century such as Doppler shifts in stellar spectra and deflections of falling bodies came to bear.

Over the course of the years human ingenuity and reason have triumphed over ignorance. Humans have interacted with nature in a variety of forms – the formulations of principles and laws from observations, the creation and development of hypothesis, and ultimately theory formation. These all require creativity and increasingly sophisticated forms of observation that includes technology, and give rise to a more and more sophisticated understanding of nature. This is in no way more true than in the development of theories. Theories are the hallmark of scientific understanding. They are consistent with established knowledge, they unify data and account for hitherto unexplained data, they sometimes point to relationships that previously have gone unnoticed, they explain and often predict. These are all hallmarks of Darwin's theory of Evolution, Mendeleev's periodic table, Wegener's theory of plate tectonics, Einstein's theory of Special Relativity, and Watson and Crick's Double Helix model of DNA. The theories of science represent the pinnacle of scientific knowledge, yet they all are subject to judgment and revision in light of new scientific evidence.

### Scope and Limitation of Scientific Knowledge

Scientific knowledge, because its conclusions ultimately are based on empirical evidence, cannot provide answers to questions that do not have an empirical basis. Science cannot, for instance, determine the number of angels that can dance upon the head of a pin; neither can it prove nor disprove the existence of a god. It cannot deal with questions of faith or morals, or controversial subject topics such as eugenics, stem cell research, abortion, and so forth. It cannot be used to make human value judgments. It can, however, inform these decisions by providing appropriate information that can be used in making decisions about these issues. As science teachers, we must be careful not to overstep the bounds established by reliance on human reason and empirical evidence. We must be careful to avoid letting our students feel as through science can solve all problems.

Some statements that scientists accept as correct at first appear to be scientific but are not because they can be shown to be falsifiable. (Note that a statement does not have to be correct to be scientific under Popper's principle of falsifiability. See Popper, 1963.) For instance, consider the following statement derived from induction, "All copper conducts electricity". As surprising as it might seem, this is not a scientific statement because it cannot be refuted. This statement can be proven if and only if all copper everywhere in the universe has been tested. This is a practical impossibility. The statement that all copper conducts electricity can be refuted with but a single case – which has yet to be found. Still, to find this single case might take an untold amount of time. Pragmatic vindication of induction, however, is possible. Scientists have decided to believe that the results of induction are correct because we presume that the entire population has the same traits as exhibited in a sample. This is the Uniformity of Nature principle, and is a presumption upon which all scientific knowledge rests.

Even simple scientific laws such as $\Delta V=IR$ have their limitations, but these limitations are often left unstated. Consider, for instance, a 750-Watt bread toaster. At 120 volts this toaster draws 6.25 amperes implying an internal resistance of 19Ω. Could one reasonably expect to use a standard 9-volt battery to power this toaster? Why or why not? If one were to use a 9-volt battery, it would have to supply nearly ½ amp of current, something far beyond the capacity of the battery to provide. A battery of this type in this situation would be considered "non-Ohmic" as Ohm's law fails to hold for this combination of circuit elements. Similarly, a light bulb filament – as it passes from a non-glowing state to a glowing state – has a significant change of resistance during the "turn on" phase. The tungsten that makes up the bulb has a resistance that is temperature dependent. Hence, a statement of the resistance of a length of filament $L$ and cross section $A$ whose resistivity is $\rho$ would be more complex than the commonly stated law

$$R = \frac{\rho L}{A}$$

Likewise, experimental test results that corroborate a hypothesis or theory do not prove that it is correct; rather, what it implies is that the hypothesis or theory has not yet been shown to be false. When experimental evidence shows that predictions turn out to be wrong, then the hypothesis or theory from which they are generated is shown to be either incomplete or wrong. Like the principles or laws, corroboration of a hypothesis or theory has nothing to do with its confirmation.

The verification process used in science is much more extensive than in the example with apples. Scientific verification procedures are intentional, intense, and international in scope. All laws generated through induction must be put to every conceivable test and under varying conditions on a universal basis before it is said to be worthy of such a name. Even so, statements derived from induction will always be subject to doubt and can never provide us with absolute certainty. Nonetheless, we apply principles, laws, hypotheses and theories as though they are correct beyond any reasonable doubt. This pragmatic approach is taken because work on a day-to-day basis does not necessarily depend upon absolute certainty. Suffice it to say that established scientific opinion is an adequate basis for most action as evidence has shown.

Lastly, we must be careful to properly understand an authentic meaning of the word "explanation" in science. Sometimes it is stated that the reason an object at rest remains at rest or an object in motion retains the same state of motion unless some unbalanced force is acting upon is it due to inertia. At other times it is noted that bodies gravitate toward one another due to gravitational forces. Both "inertia" and "gravity" are pseudo-explanations. These terms are just different labels for the facts stated in the principles so expressed. Explanations must in a sense be "more general" than the phenomena being explained (Nagel, 1961).

### Implications for Teaching High School Physics

So what does scientific epistemology have to do with teaching high school physics, or any other science at this level? The author has heard this question from both physics teacher candidates and inservice physics teachers. The answer to this question is very important, and should not be left to the inference of the reader. Simply put, the answer is this. An understanding of scientific epistemology should have an influence on the way one teaches.

Consider the traditional lecture-based physics classroom. What do we see? In many cases the course mostly appears to revolve around two teaching/learning strategies, lectures by the teacher and reading of the textbook by the student. If one is lucky in such a classroom, every once in a while there will be a demonstration or a confirmatory lab in which students replicate an experiment following explicit instructions showing that the instructor or textbook is "correct". Now, compare this to religion. Typically learning is based on teaching from sacred texts (e.g., Torah, Bible, Koran, etc.) and a preacher (rabbi, minister or priest, mullah, etc.) explaining the content therein. When science teachers base student learning primarily on a textbook and lecture, aren't they essentially preaching "faith" in science based upon authority rather than science as an active mode of inquiry? Science is both a body of knowledge and a way of knowing. To teach the content of science without the process is to teach history, not an active pursuit of scientific knowledge.

If a teacher is to teach in a way that is consistent with scientific ways of knowing, then he or she must help students to construct knowledge and understanding from their experiences. The teacher's method should consistent largely of asking questions, and guiding students in such a way as to find answers to their questions. The students will learn when their attention is directed to certain points focusing on relevant information, and drawing conclusions. It's only when one helps another to see things with his own eyes that he can be said to be a teacher. Still, we must be careful not to allow the educational pendulum swing too far one way. Science teaching should not be thought of as an either/or situation, inquiry-oriented versus transmission-oriented instruction. Both have their place in implementation of the curriculum.

Still, teaching on the basis of authority, even in science, has its benefits. Nowhere more clearly can this seen than in post-introductory courses in science. It would be unreasonable in these courses to think that every result should be based on first-hand experiences and experiments. At some point students have to understand that the converged opinion of institutional science is, in the main, quite credible, but this should not be done in an introductory course where teachers need to instruct students in both the content and processes of science.

***References:***

Bronowski, J. (1965). *Science and Human Values.* New York: Julian Messner, Inc.

Chisholm, R. (1982). *The Foundations of Knowing*. Minneapolis: University of Minnesota Press.

Gettier, E. (1963). Is justified true belief knowledge?, *Analysis,* 23, 121-123.

Kuhn, T.S. (1970). *The Structure of Scientific Revolutions*, 2nd. ed., Chicago: University of Chicago Press.

Lawson, A.E. (1995). *Science Teaching and the Development of Thinking.* Belmont, CA: Wadsworth Publishing Company.

Nagel, E. (1961). *The Structure of Science: Problems in the Logic of Scientific Explanation.* New York: Harcourt, Brace & World, Inc.

Popper, K. (1963). *Conjectures and Refutations: The Growth of Scientific Knowledge,* London: Routledge.

Wenning, C.J. (2005). Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes. *Journal of Physics Teacher Education Online,* 2(3), 3-1.

## Solutions of problems “left to the student”.

$$v = v_0 + at$$

$$vt = v_0 t + at^2$$

now, $d = d_0 + v_0 t + \frac{1}{2} at^2$

$$2(d - d_0) = 2v_0 t + at^2$$

$$2(d - d_0) - 2v_0 t = at^2$$

hence, $vt = v_0 t + 2(d - d_0) - 2v_0 t$

$$vt = 2(d - d_0) - v_0 t$$

$$vt + v_0 t = 2(d - d_0)$$

$$F \frac{vt}{2} + F \frac{v_0 t}{2} = F(d - d_0)$$

$$\frac{mavt}{2} + \frac{mav_0 t}{2} = W$$

$$\frac{mat}{2}(v + v_0) = W$$

now, $v - v_0 = at$

$$\frac{m}{2}(v - v_0)(v + v_0) = W$$

$$\frac{m}{2}(v^2 + vv_0 - vv_0 - v_0^2) = W$$

$$\frac{m}{2}(v^2 - v_0^2) = W$$

$$\frac{1}{2} mv^2 - \frac{1}{2} mv_0^2 = W$$

$$\Delta E = W$$

$$d - d_0 = \bar{v}(t - t_0)$$

$d - d_0 = \frac{(v + v_0)}{2} t$ where $t_0 = 0$

$$F(d - d_0) = \frac{ma(v + v_0)}{2} t$$

$$W = \frac{1}{2} mvat + \frac{1}{2} mv_0 at$$

but, $v - v_0 = at$

$$W = \frac{1}{2} mv(v - v_0) + \frac{1}{2} mv_0 (v - v_0)$$

$$W = \frac{1}{2} mv^2 - \frac{1}{2} mvv_0 - \frac{1}{2} mv_0^2 + \frac{1}{2} mvv_0$$

$$W = \frac{1}{2} mv^2 - \frac{1}{2} mv_0^2$$

$$W = \Delta E$$

# Connecting three pivotal concepts in K-12 science state standards and maps of conceptual growth to research in physics education

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*This paper describes three conceptual areas in physics that are particularly important targets for educational interventions in K-12 science. These conceptual areas are force and motion, conservation of energy, and geometrical optics, which were prominent in the US national and four US state standards that we examined. The four US state standards that were analyzed to explore the extent to which the K-12 science standards differ in different states were selected to include states in different geographic regions and of different sizes. The three conceptual areas that were common to all the four state standards are conceptual building blocks for other science concepts covered in the K-12 curriculum. Since these three areas have been found to be ripe with deep student misconceptions that are resilient to conventional physics instruction, the nature of difficulties in these areas is described in some depth, along with pointers towards approaches that have met with some success in each conceptual area.*

## *Introduction*

Connecting the K-12 science standards and maps of conceptual growth to research on common difficulties and strategies for helping students develop a good grasp of the pivotal concepts is critical for ensuring that our K-12 students master the concepts. This connection between the standards and research on student difficulties in learning the concepts can help all stakeholders including teachers who can incorporate them in instruction, and science faculty members planning professional development activities for K-12 teachers because they may not necessarily know the links between different conceptual areas of science and the standards.

Unfortunately, K-12 science curricula have often been described as being a mile wide and an inch deep (Frelindich, 1998), leaving students with little understanding of or interest in science. The problem is further intensified because many elementary teachers are teaching science with little background in science, and many middle school and high school science teachers are teaching out of field (Ingersoll, 2003; Shugart & Houshell, 1995), or perhaps with out-of-date knowledge (Griffith & Brem, 2004). Thus, it is very difficult to provide good professional development for science teachers on so many different science topics.

One possible solution is to emphasize fewer topics. Indeed, the AAAS Project 2061 Benchmarks for Science focus on a smaller set of coherent themes that are typically covered in many K-12 science courses. There are many benefits of having a smaller set of topics to teach: science education researchers can focus their research efforts to analyze and understand the learning issues on a more focused set of concepts; science curriculum developers can develop curriculum with greater research support and more focused testing; faculty members involved in teacher preparation can focus their in-service and pre-service professional development activities on thoughtfully prepared and tested strategies; teachers can spend time exploring the interplay of science processes and science content with their students rather than racing through a textbook of science facts and stories; and students can come to deeply understand and appreciate science as a way of thinking and interacting with the world around them (Lederman, 1992).

Unfortunately, the majority of the state science standards in the US have much broader content coverage than the AAAS Benchmarks for Science. The current climate for K-12 science education in the US is one of high stakes accountability under the No Child Left Behind legislation. Because performance on state standardized test is a key variable, and because the tests focus solely on broad state-specific standards, the pressure on students, science teachers, school districts, schools of education, and curriculum developers continues to be in the direction of breadth of coverage.

Despite such pressure, there is room in the K-12 science curriculum for higher quality science experiences that can help students develop problem solving and reasoning abilities. There are some foundational science concepts that have more overall influence on student performance than others, and high quality experiences could be created to enable the learning of these concepts. Some research-based materials that provide such experiences have already been created. It is their effective implementation in K-12 education that remains problematic. The focus of the current paper is to explore this conjecture in the context of physics. Specifically we ask whether there are a set of physics concepts that are widely found in state standards, are foundational for later learning of other K-12 science concepts, and are traditionally very difficult to learn.

With such information in hand, faculty members involved in teacher preparation, curriculum developers, and teachers could be better informed about what physics concepts are worthy of extended inquiry which is a key decision when using inquiry-based approaches for improving students' learning. Science teachers who are

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typically required to update their knowledge with ongoing professional development (Fishman, Marx, Best, & Tal, 2003) will also find this paper useful. This paper tries to capture the core K-12 learning challenges of physics, bridging the often disparate worlds of high stakes accountability, deep science disciplinary perspectives, and learning challenges.

### *Analyzing State Standards with a Focus on Physics*

From our analysis of standards and curricula in the US, physics and chemistry are usually treated together through the elementary years under the label of physical sciences, and typically with considerably less emphasis than the coverage devoted to biology and earth science concepts. In the middle school years, physics and chemistry emerge as separate but related disciplines. In high school, physics and chemistry are treated as entirely disconnected, although to physicists, the same underlying physics concepts can be found in high school chemistry, biology, and earth science courses (e.g., conservation of energy, forces in equilibrium).

In this paper, we present a three-part analysis of the conceptual landscape in K-12 physics. In the first part of the analysis, we examined concept maps—some from the Science Atlas created by Project 2061 and some developed by us when they were not available in the Science Atlas—of different conceptual clusters that plot how physics concepts in the K-12 curriculum are related to one another. We looked for concepts that were pivotal nodes within the maps. In other words, we looked for concepts that were foundational to many other related concepts. Since the structure of physics is very hierarchical, there are deep connections within K-12 physics, with cross-connections between sub-areas of physics (e.g., between forces and motion, conservation of energy, and electricity and magnetism). Similarly there are important connections and bridges to other K-12 sciences. Without engaging in scientific reductionism, one can note that all of the concepts that are shared across the K-12 sciences (except for the process ideas) are essentially physics concepts (e.g., conservation of energy).

In the second part of the analysis, we examined state science standards from four states representing a wide range of state standards. With only 4 states, one cannot be exhaustive, but we tried to cover the following dimensions: very large, very small, and mid-sized states (reflecting differential resources in the construction of standards); and West, Central, and East states (reflecting different values from historical populations and industries). But most importantly, we tried to cover states that had very different styles of standards. The states we selected and their standard style included: California (extremely detailed, very fact oriented, organized by grade level), Colorado (mostly conceptual, organized by discipline and grade groups 4-8-12), Rhode Island (moderately detailed on a more select set of concepts, based on Project 2061, organized by themes and grade groups 2-5-8-12), and Wisconsin (extremely conceptual, organized by discipline, grade 4-8-12, and theme). We looked for concepts that were prominently found (i.e., as full standards on their own, rather than buried as one minor example in another standard) in the science standards for all four states, and at the same approximate level (e.g., at the middle school level).

It should be noted that physics is the oldest and most basic science, and thus one may expect the topics for inclusion into K-12 physics courses to be relatively stable. Indeed, physics K-12 content involves mostly scientific work from over 100 years ago, and not for historical reasons but rather because the core classical physics knowledge has not seen much change. By contrast biology has seen an explosion in the amount of knowledge known in the last 20 years, e.g., knowledge related to the human genome, and these changes are reflected in the curriculum. Interestingly, even in physics, there is only moderate agreement across state standards in content coverage. Some big ideas (e.g., magnetism) are found in elementary standards in one state and in high school standards in another state. Some big ideas are completely absent in some state standards. For example, electricity concepts are not universally found in state standards.

In the third part of the analysis, we examined the research literature on difficulties in learning physics to determine why pivotal physics concepts in the state standards are challenging for students to learn and research-based strategies that have been found successful.

The physics at the high school level demands a certain level of mathematical sophistication and quantitative expertise in at least algebra and trigonometry to avoid cognitive overload (Larkin, McDermott, Simon & Simon, 1980; Singh, 2002a; Singh, 2008b). The mathematics in physics often represents a serious challenge for many students (Reif, 1981; Larkin & Reif, 1979; Singh, 2004). However, the third part of our analysis focused on conceptual difficulties in learning physics. Regardless of how proficient students are in quantitative analysis, conceptual understanding is necessary to be able to perform quantitative analysis beyond guessing or "plug and chug" (Mazur, 1997; Kim & Pak, 2002; McDermott, 2001; Singh, 2008a, 2008c). Research shows that even honors students have conceptual difficulties in learning physics (e.g., difficulty in distinguishing between displacement, velocity and acceleration) similar to the general student population (Peters, 1982).

Finally, we sought those physics concepts that were salient in all three steps: conceptually pivotal, found in all four state standards, and particularly difficult to learn. Three concepts emerged: Newton's laws (qualitatively only at the middle school level or qualitative and quantitative at the high school level), conservation of energy (at the high school level) and geometrical optics (at middle and high school levels). No other concepts came close to meeting all three criteria.

The remainder of this paper presents the case for each of these three concepts. Each section begins a discussion of the role of the identified concept in the broader conceptual landscape. Second, there is a brief discussion of how state standards talk about the concept and at what level (high school or middle school) the concept can be commonly found. Third, there is an in-depth discussion of what makes that particular concept difficult to learn, as a resource for teachers, those involved in professional development, and curriculum developers. Finally, there is brief mention of approaches that have seen some success in teaching particular concepts.

### *Newton's Laws*

Force and motion are fundamental concepts in all sciences and are related to diverse physical phenomena in everyday experience. These concepts provide the backbone on which many other science concepts are developed. According to the Atlas of Science Literacy Project 2061 Motion maps (see Appendix A), children in grades K-2 should be given an opportunity to learn about various types of motion e.g., straight, zigzag, round and round, back and forth, fast and slow and how giving something a push or a pull can change the motion. The map shows a gradual transition to helping students develop more sophisticated ways of thinking about forces and motion in later grades. For example, children in grades 3-5 should be taught how forces cause changes in the speed or direction of motion of an object and a greater force will lead to a larger change in these quantities. Children in 6-8 grades should learn Newton's laws, relative velocity concepts, and their implication for motion with a central force (e.g., planetary motion) mostly qualitatively while those in grades 9-12 should learn these concepts more elaborately and quantitatively.

In the map in Appendix A, the concepts that are a component of Newton's laws are indicated in italics. In the middle grades, there is a recommended emphasis on a qualitative understanding of Newton's laws, followed by a quantitative understanding in high school. It is important to note that the qualitative understanding of Newton's laws, and to some extent the quantitative understanding of Newton's laws is the foundation of many other related concepts.

Turning to the state science standards, one finds that only Newton's second law (F=ma), of all force and motion concepts, is found consistently in the standards. Table A1 presents the relevant state science standards. At the middle school level, the required understanding is very qualitative, and thus the language does not directly refer to the law itself. It is interesting to note that in the Colorado and Wisconsin standards, the language in the standards is so general for the relevant middle school standards that a variety of force and motion concepts at the qualitative level are invoked, and only a person very knowledgeable in physics is likely to realize that Newton's second law is highly relevant here.

At the high school level, the relevant science standards are much more quantitative and specific to Newton's second law, although only the California standards have the actual equation and name the law specifically. Rhode Island standards describe the key quantitative relationship in the law in words rather than in an equation. Colorado and Wisconsin standards again use very abstract terms such that only a person very knowledgeable in physics would realize that Newton's laws were being invoked.

The standards particularly emphasize Newton's second law. However, since all the three laws of motion are intertwined, an understanding of all the three laws of motion is necessary for a good understanding of force and motion. Therefore, we will discuss all the three laws of motion in some detail.

Unfortunately, the teaching of force and motion concepts is quite challenging (Camp & Clement, 1994; Champagne, Klopfer & Anderson, 1980; Clement, 1983; Halloun & Hestenes, 1985a, Halloun & Hestenes, 1985b; McDermott, 1984; McDermott, 2001; Singh, 2007). Students are not blank slates. They constantly try to make sense of the world around them. Since force and motion concepts are encountered frequently in everyday experiences, people try to rationalize their experiences based upon their prior knowledge, even without formal instruction. According to Simon's theory of bounded rationality (Simon, 1983; Simon & Kaplan, 1989), when rationalizing the cause for a phenomenon, people only contemplate a few possibilities that do not cause a cognitive overload and appear consistent with their experience. Accordingly, students build "micro" knowledge structures about force and motion that appears locally consistent to them but are not globally consistent. These locally consistent naive theories due to mis-encoding and inappropriate transfer of observation are termed "facets" by Minstrell (1992) and "phenomenological primitives" by diSessa (Smith, diSessa & Roschelle, 1993).

Cognitive theory suggests that preconceptions and difficulties about a certain concept are not as varied as one may imagine because most people's everyday experiences and sense-making is very similar (Reason, 1990; Tversky & Kahneman, 1974). Therefore, regardless of the grade-level in which force and motion concepts are taught, most students have similar preconceptions about motion and forces (Camp & Clement, 1994; Champagne, Klopfer & Anderson, 1980; Clement, 1983; Halloun & Hestenes, 1985a, Halloun & Hestenes, 1985b; McDermott, 1984; McDermott, 2001; Singh, 2007). For example, contrary to the Newtonian view, a majority of students believe that motion implies force and an object moving at a constant velocity must have a net force acting on it. This is an over-generalization of the everyday observation that if an object is at rest, a force is required to set it in motion. Due to the presence of frictional forces in everyday life, such preconceptions are reinforced further, e.g., in order to make a car or a box move at a constant velocity on a horizontal surface one needs to apply a force to counteract the frictional forces. These observations are often interpreted to mean that there is a net force required to keep an object in motion. Research has shown that these preconceptions are very robust, interfere with learning, and are extremely difficult to change without proper intervention (Arons, 1990; Camp & Clement, 1994; Champagne, Klopfer, & Anderson, 1980; McDermott, 1991; McDermott, 1993). They make the learning of the Newtonian view of force and motion very challenging, and old conceptions often reappear after a short time.

In fact, the concepts of force and motion proved very challenging to early scientists prior to Newton and Galileo. Halloun and Hestenes (1985a) discuss how the great intellectual struggles of the past provide valuable insight into the conceptual difficulties of students learning these concepts. The common sense notion of many beginning students conforms more with the medieval Impetus theory of force and motion, than with the Aristotelian view (Halloun & Hestenes, 1985a, 1985b). Students who hold the impetus view tend to believe that if a baseball is hit by a bat, the force of the hit is still acting on the ball long after the ball has left contact with the bat and is in the air.

Research has shown that even after instruction, students' views about force and motion is context dependent and many students solve problems using the correct Newtonian principles under certain contexts while choosing non-Newtonian choices under other contexts (Camp & Clement, 1994; Champagne, Klopfer & Anderson, 1980; Clement, 1983; Halloun & Hestenes, 1985a, 1985b; McDermott, 1984; McDermott, 2001; Singh, 2007). For example, students may cite Newton's first law to claim that an object moving at a constant velocity in outer space (where there is nothing but vacuum) has no net force acting on it but claim that there must be a net force on an object moving at a constant velocity on earth. Many students incorrectly believe that Newton's first law cannot hold on earth due to the presence of friction and air-resistance. Similarly, even after instruction in Newton's third law, students have great difficulty recognizing its significance in concrete situations (Halloun & Hestenes, 1985a, Hammer & Elby, 2003, Mazur, 1997). For example, if students are asked a question involving collision of a small car and a big truck after instruction in Newton's third law, a majority believes that the big truck will exert a larger force on the small car. This conception is due to the confusion between force and acceleration (Halloun & Hestenes, 1985a, Hammer & Elby, 2003, Mazur, 1997). Although the magnitude of the force exerted by the big truck on the small car is equal to the magnitude of the force exerted by the small car on big truck, according to Newton's second law, the acceleration of the small car will be more. Therefore, the small car will get damaged more in the collision despite the fact that forces are equal on both car and truck.

Newton's laws are very difficult to teach because there are in fact several distinct preconceptions at play, each of which manifests themselves in many different ways (Halloun & Hestenes 1985a,1985b; Hammer & Elby, 2003, McDermott, 2001). In the sections that follow, we describe some of these difficulties and illustrate the diverse ways in which they manifest themselves.

### ***Incorrect Linkage of Force and Velocity Concepts***

Students often confuse velocity and acceleration and believe that the net force on an object is proportional to its velocity. Directly tied to this confusion, students also believe that there must be a force in the direction of motion. Clement (1983) performed a study in which he asked first year college students enrolled in a pre-engineering course to draw a force diagram of a coin just after it has been tossed in the air. A large group of students was asked to draw the diagram on paper before and after instruction while a smaller group was presented with the same task during an interview situation. A common incorrect response was that while the coin is on the way up, the force of the hand must be greater than the gravitational force because the students believed that there must be a force in the direction of motion. Students also claimed that the force of the hand on the coin gradually dies away after the coin is launched, consistent with the "impetus" view. The confusion between velocity and net force also caused students to incorrectly claim that the net force on the coin was zero when the coin was at the highest point and on its way down the gravitational force on it is greater than the force of the hand. This confusion between velocity and net force was pervasive even after instruction. Clement extracted a number of characteristics from student responses and labeled them the "motion implies force" preconception. He noted that students who hold these views believe that a force that "dies out" or "builds up" accounts for changes in an object's speed.

Viennot (1979) used written questions to investigate high school and introductory college students' understanding of force and motion. She posed a problem in which a juggler is playing with six identical balls. At a particular instant the balls were all at the same height from the ground but had velocity vectors pointing in different directions. Students were asked if the forces on all the balls were the same or not. Approximately half of the students noted that the forces are different because of the confusion between velocity and force.

A conceptual standardized multiple-choice assessment instrument that has been used extensively in high schools and introductory college physics courses to evaluate student understanding of and misconceptions related to force and motion concepts is the Force Concept Inventory (FCI) developed by Hestenes et al. (Hestenes, 1995; Hestenes, Wells, & Swackhamer, 1992). A variety of studies with this instrument have shown that a majority of students do not develop a Newtonian view of force and motion after traditional instruction (Hake, 1998).

In one question, an elevator is being lifted up an elevator shaft at a constant speed by a steel cable. In the absence of frictional forces, students are asked to compare the upward force of the cable with the downward force of gravity. According to Newton's first law, both forces should be equal in magnitude since the elevator is moving at a constant velocity. A large number of students believe that the upward force of the cable must have a greater magnitude than the downward force of gravity because the elevator has an upward velocity.

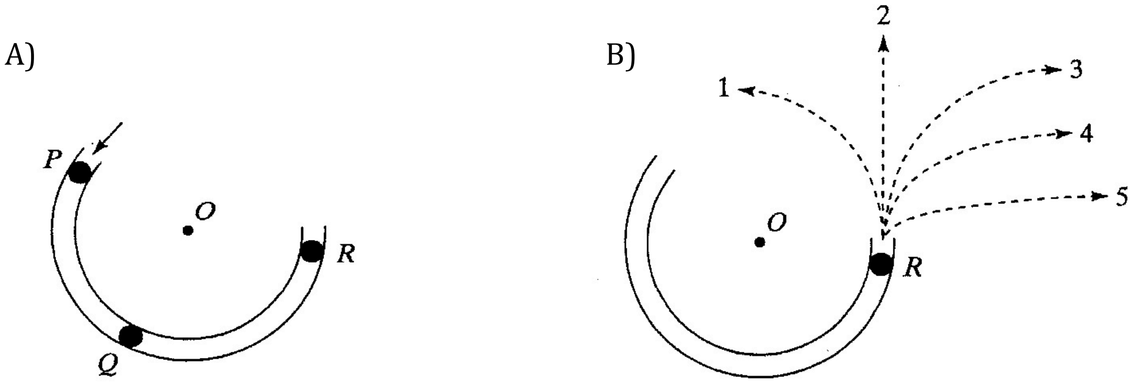


Figure 1. Illustrations of A) a ball at several points within a tube lying on a table, and B) the paths the ball could take on exiting the tube.

Related to this issue, several items on the test probe the misconceptions that there must be a force in the direction of motion and the forces 'die out" over time. One question on the test has a frictionless channel in the shape of a segment of a circle as shown in Figure 1A. The question notes that the channel has been anchored to a frictionless horizontal tabletop and you are looking down at the table. A ball is shot at high speed into the channel at P and exits at R. Ignoring the forces exerted by air, students are asked to determine which forces are acting on the ball when it is at point Q within the frictionless channel. A very strong distracter is "a force in the direction of motion" which is selected frequently by students. The second part of the question asks for the path of the ball after it exits the channel at R and moves across the frictionless tabletop. According to Newton's first law, the correct response is path (2) as shown in Figure 1B because the net horizontal force on the ball is zero after it exits the channel. The most common distracter consistent with the response to the previous question is path (1) because students believe that there is a force on the ball in the direction of motion that should continue to keep it along the circular path even after it exits the channel.

This bizarre circular conception of impetus is not specific to circular motion in a tube. In another question, students have to predict the path of a steel ball attached to a string that is swung in a circular path in the horizontal plane and then the string suddenly breaks near the ball (Figure 2). A large number of students choose distracter (1) instead of the correct response (2) even after instruction in Newtonian physics.

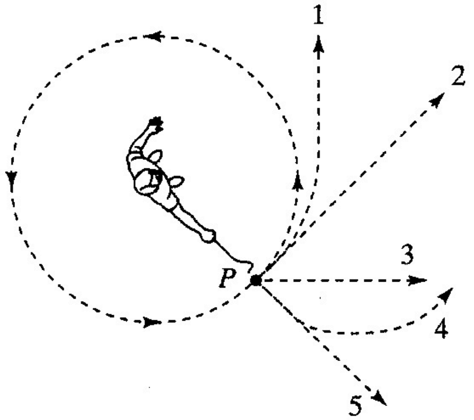


Figure 2. Possible paths taken by a ball swung around on a string and launched at point P.

The problem of impetus conceptions can also be thought of as a confusion between velocity and acceleration. This confusion between velocity and acceleration is illustrated by a question in the FCI in which students are given the position of two blocks at 0.2-second time interval and are asked to compare their accelerations (Figure 3). Neither block has any acceleration because their displacements are equal in equal times. However, a large number of students believe that the block with a larger speed must have a larger acceleration.

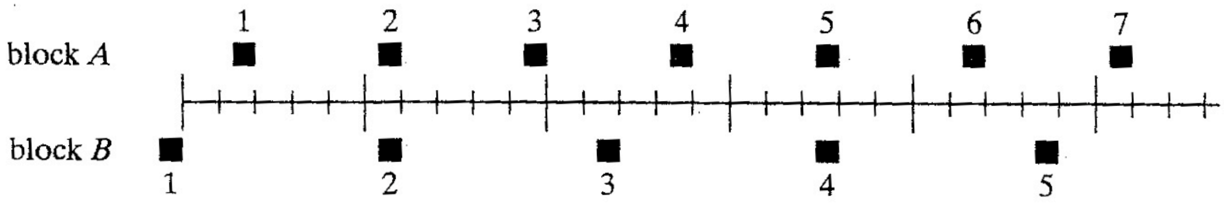


Figure 3. The positions of two blocks taken at 0.2-second intervals.

McDermott et al. (McDermott, 1984; Trowbridge & McDermott, 1981) have shown that in fact the confusion is between displacement, instantaneous velocity (or simply the velocity), and instantaneous acceleration (or simply the acceleration) of an object. One investigation involved asking students to compare the acceleration of two balls sliding down two tracks and whether the accelerations were ever equal for the two balls. About half the students incorrectly claimed that the acceleration would be the same for the two balls at the same point where the velocities of the balls were equal. When the interviewer asked for reasoning, a typical response was that since the acceleration is the change in velocity over time, at the point where the velocity were the same, the rate of change of velocity will be the same as well. Students claimed that since the change in time is the same in both cases, the acceleration at that instant should be the same. This is obviously not correct, because while one can talk about velocity at one position, acceleration is determined by looking at velocity at two different locations (which can be infinitesimally close). In fact, if an object with a zero velocity could not have a non-zero acceleration, the object would never start moving from rest. Part of the difficulty could be due to the confusion between the instantaneous values of velocity and acceleration and their average values for some elapsed time especially for cases where the objects start from rest and are moving in one dimension.

The impetus misconception also relates to weight/mass confusion. For example, one pervasive naive belief is that the rate at which things fall under the gravitational force is dependent on their weight. There are several items on the FCI that probe this misconception (Hestenes, 1995; Hestenes, et al., 1992). For example, when two balls with different mass are dropped from the same height both balls should take the same time because they both fall under the same gravitational acceleration. A common misconception is that the heavier ball will reach the bottom faster. Another question on the FCI test asks students to compare the horizontal distance from the base of the table covered by metal balls with different masses when they are rolled off a horizontal table with the same speed. The correct response is that both balls should hit the ground at the same horizontal distance from the table but many students incorrectly believe that the heavier ball will fall horizontally farther due to its greater weight.

Singh has developed several explorations (Singh, 2000; 2002b) that greatly improve student understanding of concepts related to force and motion. All the explorations begin by asking students to predict what should happen in a particular situation in which misconceptions are prevalent. For example, the exploration that challenges students' belief that the force of hand still acts on an object after the object is no longer in touch with the hand begins with the following question: "When a baseball soars in the sky after being hit by a bat, the force of the hit still acts on the ball after it has left contact with the bat". Do you agree or disagree with this statement? Explain." After answering this warm-up question, students perform an exploration on a frictionless horizontal air-track. They are asked to push a slider on the track with different initial velocity and then record the velocity and acceleration using a motion sensor and computer. Students are asked to interpret their graph that shows that the velocity is more in the case in which greater initial force was applied to the slider but the acceleration of the slider on the horizontal air-track remains zero for all these cases. They are then asked to interpret what zero acceleration implies about the net force on the object according to Newton's second law. A majority of the students are able to rationalize that the net force on the slider must be zero if the acceleration is zero. They are then asked how this is possible and what it means about the initial force of the hand they applied to make the slider move. Most students are able to interpret that the force of the hand does not act on the slider once it has been let go.

Then students are asked to re-evaluate their initial response to the baseball question and whether the force of the hand still acts on it after once it has been let go.

Another exploration helps students understand that the net force is NOT proportional to velocity and helps them distinguish between acceleration, velocity and displacement. Students are given a situation in which two friends are driving in parallel lanes. One person is going at a constant velocity of 30 m/s while another person starts from rest and is accelerating at 1m/s$^2$. They cross at some point. Students are asked about which variables (acceleration, velocity or displacement) are the same for both friends when they cross. Students perform this exploration with sliders on parallel air tracks in which they observe using motion sensors and computer graphs that while displacements are the same, the velocity and acceleration are not the same when the two sliders cross. Students rationalize these observations and learn to make distinction between different variables related to motion. This type of exploration can also be helpful in teaching students about the difference between the instantaneous and average velocities.

Another exploration helps students understand that an object dropped from a moving car or airplane has the same horizontal velocity as the car or airplane. Students start the exploration by answering the following question: Predict whether a ball dropped from your hands while you are standing on a moving walkway at the airport will fall behind you, in front of you, or next to you ignoring air-resistance. Then students perform an exploration with a ball launcher moving at a constant velocity on a horizontal air-track. They find that the ball launched vertically from the launcher follows a parabolic path and falls back in the launcher. They have to interpret what it means about the horizontal velocity of the ball after it is launched and the forces acting on it. After the exploration, a majority of the students are able to explain that the ball dropped from a moving walkway will fall next to the person because the ball has the same horizontal velocity as the person.

### *Difficulty in Understanding the Components of the Net Force*

Students often have difficulty figuring out the individual forces acting on an object. This skill is vital for applying Newton's laws and for appropriately determining the net force in various situations. Minstrell (1982) performed a study investigating high school students' preconceptions about what was keeping a book at rest. Many students drew and labeled diagrams that depicted air pressing in from all sides while others noted that air was mainly pressing down on the book. Some students noted that air pressure was helping gravity hold the book down and some explicitly noted that if air was taken away, the book might drift off. Nearly all students invoked gravity but some students thought of gravitational force as a tendency of an object to go down as opposed to the pull of the earth. Only half the students noted that the table exerts an upward force on the book. For the others, the table was incapable of exerting a force; it was simply in the way. Minstrell's modified instruction, which was reasonably successful, included discussions of an object placed on a helical spring, why the spring compresses and its implications for an upward force on the object by the spring.

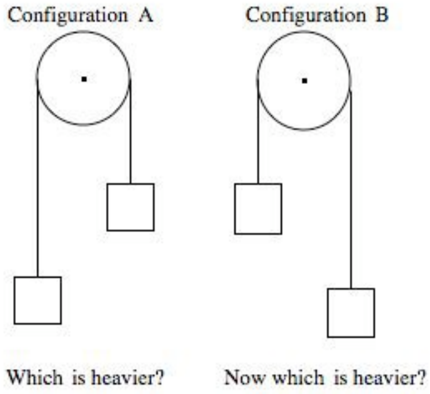


Figure 4. Example Atwood machine configurations with blocks at rest, but with blocks in different locations. Reprinted with permission from Mestre, J. & Tougher, J. Cognitive research--What's in it for physics teachers? The Physics Teacher. 1989, American Association of Physics Teachers.

One common factor involved with difficulties in analyzing the components of a net force is the tendency of beginning students to focus on the surface features of the problem to draw inferences (Mestre & Tougher, 1989, Singh, 2007). The lack of focus on deep features is well illustrated in research involving the Atwood machine, which has two masses connected to each other via a weightless rope as shown in the Figure 4. Research has found that if the rope is lower on one side of the Atwood machine than the other and the whole system is at rest, students predict that the mass on the lower side must be larger (Mestre & Touger, 1989).

In a slightly different version of the set up, researchers clamped the masses at the ends of the rope in the Atwood machine set up, drew students' attention to the fact that the masses on the two sides of the rope were the same (even though they had different sizes) and then asked them to predict what would happen to the masses after un-clamping them. A majority of students predicted that the smaller mass will accelerate downward and the larger mass will accelerate upward. This prediction is in contradiction with the Newtonian analysis in which the net force on each identical mass is zero so there is no acceleration. Therefore, the masses should remain at rest even after the clamp is removed.

There are a variety of techniques that help students correctly analyze the individual components of a net force. Mestre et al. (1989) argue that these kinds of demonstrations, if preceded by the prediction phase, can be powerful tools for creating a state of disequilibrium in students' minds (Ginsberg & Opper, 1969; Gorman, 1972). Following this view, if students are given appropriate guidance and support to assimilate and accommodate Newtonian views about force and motion using free body diagrams, they are likely to be successful (Posner, Strike, Hewson & Gertzog, 1982).

Sokoloff and Thornton (1997) also argue that students are better able to develop Newtonian views of force and motion by preceding lecture demonstrations with a prediction phase. They developed a large number of interactive lecture demonstrations that give students an opportunity to predict the outcome of experiments. The outcomes of these demonstrations often contradict common sense notions and challenge students to resolve the inconsistencies in their prior knowledge and what they observed. Students are then guided through a set of exercises that help them resolve the inconsistencies and build robust knowledge structure. Thornton and Sokoloff have also designed a standardized assessment tool called Force and Motion Conceptual Survey that can be given as a pre- and post-test to assess the extent to which students have developed Newtonian views of force and motion (Thornton & Sokoloff, 1998).

### *Difficulty with the Vector Nature of Variables*

Student difficulty with force and motion is also due to the difficulty with the vector nature of some kinematics and dynamics variables (Aguirre, 1988; Aguirre & Erickson, 1984; Helm & Novak, 1983; Saltiel & Maigrange, 1980). Force, acceleration, velocity and displacement are all vector quantities. Addition of these variables involves knowledge of vector addition and notion of reference frames. In the FCI test, one question asks students about the path of a hockey puck moving horizontally after a force perpendicular to the direction of its velocity is applied to it at an instant. Rather than vectorially accounting for the original velocity, many students believe that the puck will immediately start moving in the direction of the applied force.

McClosley, Caramazza and Green (1980) performed a study in which they asked students who were enrolled in the introductory college physics courses about the path (trajectory) of a pendulum bob after the string was cut when the pendulum was at four different points during its oscillatory motion. Only one fourth of the students provided the correct response for all the four points of the bob. A majority of students ignored the velocity of the bob at the instant the string was cut and 65% noted that the bob would fall straight down (as though it was at rest) when the string was cut at the instant it was passing through its equilibrium position during the oscillatory motion.

A similar misconception is manifested in the FCI test (Hestenes, 1995; Hestenes, et al., 1992). One question in the FCI asks students about the trajectory of a ball dropped from an airplane that is moving horizontally at a constant velocity ignoring air-resistance. Many students do not realize that since the ball is in the airplane when it is dropped, it has the same horizontal velocity as the plane. It should therefore fall along a parabolic path and in the absence of air resistance it should hit the ground right underneath the airplane. Many students believe that the ball would fall behind the airplane because they do not consider its horizontal velocity.

As noted earlier, Singh (2000, 2002b) has found that an exploration by students illustrating that a ball launched from a launcher moving on a horizontal track follows a parabolic path and lands back into the launcher can be an effective instructional tool if it is preceded by asking students to make a prediction about the outcome.

In sum, Newton's laws are prominent in US State science standards, are foundational concepts, and are quite difficult for students to learn, for a number of different reasons. We have further identified the kinds of experiences that have been found to help students improve their learning of these concepts.

### *Conservation of Energy*

Similar to the concepts of force and motion, energy is a fundamental concept that is useful in all sciences. The Atlas of Science Literacy Project 2061 does not have a map specifically of energy concepts. Therefore, we created our own map organizing energy concepts found in the National and State Science Standards (see Appendix B). For example, children in grades K-2 should learn about the different forms of energy e.g., sound, light, heat, nuclear, energy of motion at a level consistent with their cognitive development. Children in grades 3-5 should learn at a qualitative level consistent with their expertise that energy cannot be created or destroyed but be converted from one form to another by doing work. Children in grades 6-8 can build on the previous concepts by learning more elaborately about kinetic and potential energies, heat energy and the scientific meaning of "work" in terms of force and distance (for the case where the force and the corresponding motion are in the same direction). High school students can learn these things in greater depth and more quantitatively. For example, in addition to a more in-depth analysis of the previously learned concepts, they can learn about the differences between conservative and non-conservative forces based upon whether the work done by the force depends upon the path, difference between heat and internal energy and how the nuclear energy is harnessed by converting mass into energy using the Einstein's theory of relativity.

Within this conceptual map, it becomes apparent that the core conservation of energy concepts (indicated in italics) are pivotal in the energy conceptual map in that they support many other energy concepts. Interestingly, the map places some of these notions of conservation of energy as being most appropriate for late elementary and middle school children. However, these concepts are still quite difficult for students in college physics courses, and thus the most important point is that conservation of energy ideas are the foundation of many other energy concepts and we should employ effective strategies to teach them.

Of all the energy-related concepts, conservation of energy is the concept found most consistently within the state standards at a given level. All four state standards examined explicitly named conservation of energy at the high school level, while Rhode Island and Wisconsin standards also made some mention of conservation of energy at the middle school level. Also interestingly, neither Rhode Island nor Wisconsin standards refer to a quantitative formulation of conservation of energy ideas, whereas California and Colorado very specifically make reference to quantitative forms of energy conservation and the ability to calculate energy in various forms.

Teaching energy concepts is quite challenging at all levels of instruction (Lawson & McDermott, 1987, Van Heuvelen & Zou, 2001, Singh, 2003). Unlike the concept of force (pull or push), energy concepts are rather abstract and not very intuitive. Due to their abstractness, transfer of learning from one context to another is extremely difficult (Van Heuvelen & Zou, 2001, Singh, 2003). Beginning students often inappropriately categorize problems that can be solved easily using energy concepts because the deep feature of the problem is not discerned. One prevalent hurdle is that the surface features of the target (to which knowledge is to be transferred) do not trigger a recall from memory of the relevant knowledge of energy concepts acquired in a slightly different context. However, research shows that the ability to recognize features based upon deep physical laws improves with expertise. Chi et al. (Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Rees, 1982) performed a study in which they asked physics experts and introductory physics students to categorize a large number of mechanics problems. While experts characterized them based upon fundamental principles (e.g., Newton's second law, conservation of energy problem etc.), the classification by students was often based upon superficial features (e.g., pulley and inclined plane problem etc.).

Student difficulties with energy concepts have not been investigated as thoroughly as concepts related to force and motion. However, there are investigations that show that effective instruction in energy concepts is quite difficult (Lawson & McDermott, 1987; Singh, 2003; Van Heuvelen & Zou, 2001). Our investigation shows that introductory physics students can get easily distracted by the surface features of the problem and are often unable to employ energy concepts appropriately (Singh, 2003).

We illustrate the factors making learning of and using conservation of energy difficult by drawing heavily on results from a detailed study conducted by Singh (2003). This study designed and administered a research-based 25 item conceptual multiple-choice test about energy and momentum concepts to over a thousand students in several introductory physics courses and conducted individual in-depth interviews with several dozen students using a think-aloud protocol (Chi, 1994, 1997).

### *Difficulty Recognizing a Problem as a Conservation of Energy Problem*

Conservation of energy is very useful for making complex physics problems simple because it allows one to ignore variables whose effects are quite complex and difficult to calculate and combine. For example, many conservation of energy problems allow path traveled to be ignored. But path is very salient to students and is connected to force concepts that have been a constant focus of attention in the classroom. Thus, students focus on calculating forces along a path and fail to recognize that a simpler conservation of energy solution is possible.

Consider the following question from our study related to conservation of energy (Singh, 2003):

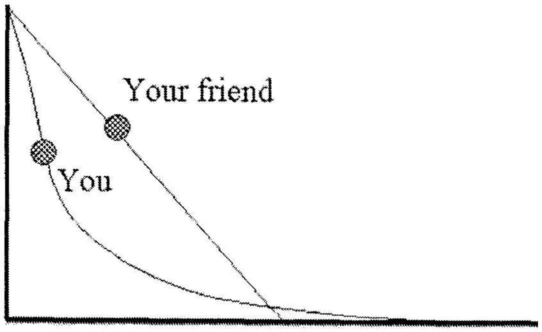


Figure 5. Frictionless slides with the same start height but different shapes. Reprinted with permission from Singh (2003).

1. Two frictionless slides are shaped differently but start at the same height $h$ and end at the same level as shown in Figure 5. You and your friend, who has the same weight as you, slide down from the top on different slides starting from rest. Which one of the following statements best describes who has a larger speed at the bottom of the slide?
   - (a) You, because you initially encounter a steeper slope so that there is more opportunity for accelerating.
   - (b) You, because you travel a longer distance so that there is more opportunity for accelerating.
   - (c) Your friend, because her slide has a constant slope so that she has more opportunity for accelerating.
   - (d) Your friend, because she travels a shorter distance so that she can conserve her kinetic energy better.
   - (e) Both of you have the same speed.

According to the principle of conservation of mechanical energy, the final speed for both people should be the same. Choices (a) and (c) were the most common distracters. It was clear that many students focused on the surface features of the problem, in particular, the shape of the slides, and did not invoke the principle of conservation of energy.

The exact same kind of results can be found when the objects are in freefall, rather than following the path of a slide. Consider the following pair of problems, illustrating that sometimes students can use conservation of energy in which the change in height is salient, but do not with a nearly identical problem in which the change in height is not salient (Note that students were asked to ignore the retarding effects of friction and air resistance).

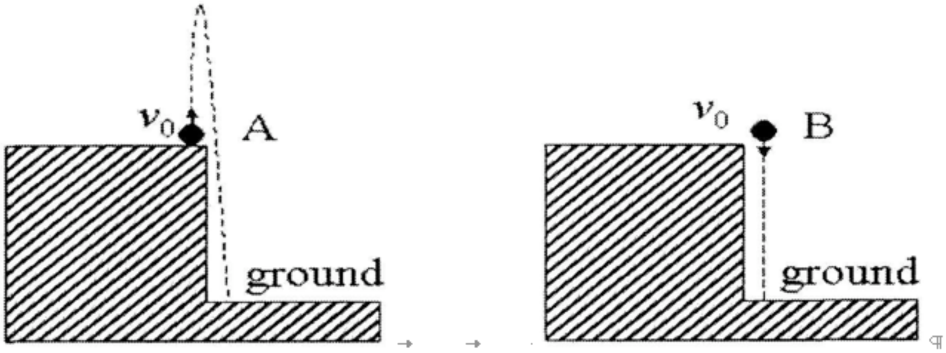


Figure 6. Paths of two identical stones shot with equal initial speed. Reprinted with permission from Singh (2003).

2. Two identical stones, A and B, are shot from a cliff from the same height and with identical initial speeds $v_0$. Stone A is shot vertically up, and stone B is shot vertically down (see Figure 6). Which one of the following statements best describes which stone has a larger speed right before it hits the ground?
   - (a) Both stones have the same speed.
   - (b) A, because it travels a longer path
   - (c) A, because it takes a longer time
   - (d) A, because it travels a longer path and takes a longer time
   - (e) B, because no work is done against gravity

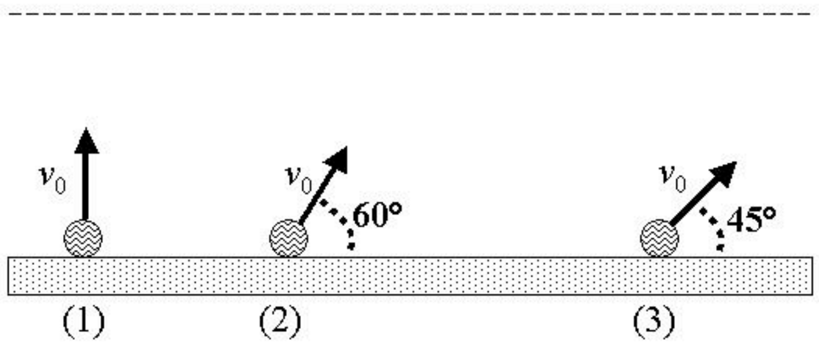


Figure 7. Three balls launched at different angles but with the same initial speed. Reprinted with permission from Singh (2003).

3. Three balls are launched from the same horizontal level with identical speeds $v_0$ as shown in Figure 7. Ball (1) is launched vertically upward, ball (2) at an angle of $60^o$ and ball (3) at an angle of $45^o$. In order of decreasing speed (fastest first), rank the speed each one attains when it reaches the level of the dashed horizontal line. All three balls have sufficient speed to reach the dashed line.
    (a) (1), (2), (3)
    (b) (1), (3), (2)
    (c) (3), (2), (1)
    (d) They all have the same speed.
    (e) Not enough information, their speeds will depend on their masses.

Using the conservation of energy, both stones in problem 2 should have the same speed and all the three balls in problem 3 should have the same speed. Students performed significantly better on problem 2 than problem 3. Problem 2 is similar to the example often presented in the textbooks. In fact, the learning gains between the pre- and post-testing (before and after instruction) was approximately three times larger for problem 2 than problem 3. A majority of students got distracted by the angles that were provided in problem 3 and did not think of using conservation of energy for that problem. Even if relevant knowledge resource about conservation of energy was present in their memory, the superfluous information about angles blocked appropriate association of this problem as a conservation of energy problem. Many started analyzing the problem vectorially, could not go too far, and came to incorrect conclusions.

Conservation of energy problems such as the following that require the student to ignore weight can also be difficult, because many students believe that weight must play a role:

4. While in a playground, you and your niece take turns sliding down a frictionless slide. Your mass is 75 kg while your little niece's mass is only 25 kg. Assume that both of you begin sliding from rest from the same height. Which one of the following statements best describes who has a larger speed at the bottom of the slide?
    (a) Both of you have the same speed at the bottom.
    (b) Your niece, because she is not pressing down against the slide as strongly so her motion is closer to freefall than yours.
    (c) You, because your greater weight causes a greater downward acceleration.
    (d) Your niece, because lighter objects are easier to accelerate.
    (e) You, because you take less time to slide down.

According to the principle of conservation of mechanical energy, the final speed for both people in problem 4 should be the same. Choice (c) was the most common distracter. Here students focused on the weight of the people sliding and did not invoke the principle of conservation of energy.

Problems involving solving for work done that involve conservation of energy also can cause problems. Consider the work done on the blocks in problem 5.

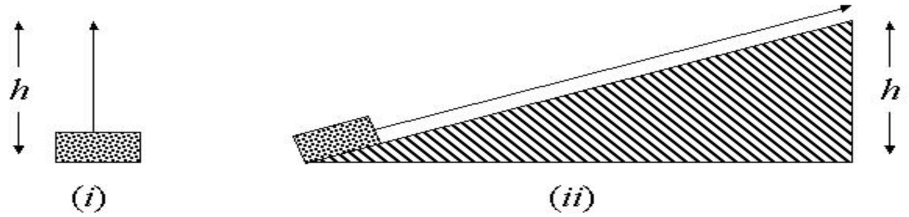


Figure 8. Blocks moved a height h at constant velocity. Reprinted with permission from Singh (2003).

5. You want to lift a heavy block through a height h by attaching a string of negligible mass to it and pulling so that it moves at a constant velocity. You have the choice of lifting it either by pulling the string vertically upward or along a frictionless inclined plane (see Figure 8). Which one of the following statements is true?
   (a) The magnitude of the tension force in the string is smaller in case (i) than in case (ii).
   (b) The magnitude of the tension force in the string is the same in both cases.
   (c) The work done on the block by the tension force is the same in both cases.
   (d) The work done on the block by the tension force is smaller in case (ii) than in case (i).
   (e) The work done on the block by gravity is smaller in case (ii) than in case (i).

Using the principle of conservation of mechanical energy, the correct response is (c). The most common incorrect responses were (d) and (e). The learning gain after instruction was very small on this item. Students had great difficulty focusing on the fact that since both blocks are raised by the same height at a constant speed, the work done by the gravitational force and tension force are the same in both cases according to the principle of conservation of energy. They got confused between the "force" and the "work done by the force" and assumed that since it is easier to pull the block along the incline surface, there must be a smaller work done in case (ii). It is clear from student responses that they ignored the fact that the distance over which the force is applied is more along the incline surface than when it is pulled straight up.

Another case of difficulty in abstracting away from details comes from having to sum the abstract concept of energy across separate objects, in other words, reasoning about a system rather than individual parts. Consider problem 6, which was very difficult for students:

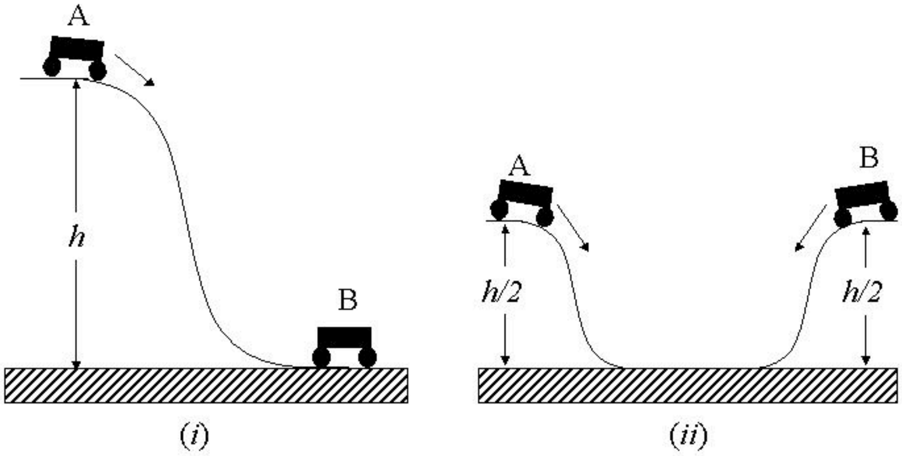


Figure 9. Carts A and B are identical in all respects before the collision. In scene (i): Cart A starts from rest on a hill at a height *h* above the ground. It rolls down and collides "head-on" with cart B that is initially at rest on the ground. The two carts stick together. In scene (ii): Carts A and B are at rest on opposite hills at heights *h*/2 above the ground. They roll down, collide "head-on" with each other on the ground and stick together. Reprinted with permission from Singh (2003).

6. Which one of the following statements is true about the two-cart system shown in Figure 9 just before the carts collide in the two cases? Just before the collision on the ground,
   (a) the kinetic energy of the system is zero in case (ii).
   (b) the kinetic energy of the system is greater in case (i) than in case (ii).
   (c) the kinetic energy of the system is the same in both cases.
   (d) the momentum of the system is greater in case (ii) than in case (i).
   (e) the momentum of the system is the same in both cases.

Using the conservation of mechanical energy, the correct response for question (6) is (c). Unfortunately, the learning gain due to instruction was negligible. Students had similar difficulties both before and after instruction and all of the alternative choices were selected with almost equal frequency.

***Confusion about Different Forms of Energy***

Our research shows that students often confuse different forms of energy, e.g., total mechanical energy, potential energy, kinetic energy, etc. This type of difficulty can make it difficult for students to be able to use the principle of conservation of energy appropriately. The response to question 7 illustrates this type of confusion (Singh, 2003):

7. Three bicycles approach a hill as described below:
(1) Cyclist 1 stops pedaling at the bottom of the hill, and her bicycle coasts up the hill.
(2) Cyclist 2 pedals so that her bicycle goes up the hill at a constant speed.
(3) Cyclist 3 pedals harder, so that her bicycle accelerates up the hill.

Ignoring the retarding effects of friction, select all the cases in which the total mechanical energy of the cyclist and bicycle is conserved.

(a) (1) only
(b) (2) only
(c) (1) and (2) only
(d) (2) and (3) only
(e) (1), (2) and (3)

The correct response to question 7 is (a) because in cases (2) and (3), the cyclist is using his internal energy to keep the bicycle moving at a constant speed or to accelerate it up the hill. Even after instruction, only 36% of the students provided the correct response. The most popular distracters were (b) and (e). Individual interviews with students who selected option (b) shows that they felt that if the bicycle moves at a constant speed up the hill, the mechanical energy must be constant. What is unchanged in case (2) is the kinetic energy of the bicycle but the total mechanical energy is increasing since the potential energy increases. The students are confusing the kinetic energy for the total mechanical energy. Students who selected choice (e) thought that the only type of force that can violate the conservation of total mechanical energy is the frictional force. They ignored the internal energy of the person pedaling and assumed that in the absence of frictional forces, the total mechanical energy must be conserved. A student who chose (e) explained: *if you ignore the retarding effects of friction, mechanical energy will be conserved no matter what.* Other interviewed students who chose (e) also suggested that the retarding effect of friction was the only force that could change the mechanical energy of the system. While some students may have chosen (b) because they could not distinguish between the kinetic and mechanical energies, the following interview excerpt shows why that option was chosen by a student despite the knowledge that kinetic and mechanical energies are different:

> *S: I think it is (b) but I don't know... it can't be (c) because the person is accelerating.., that means (d) and (e) are not right...*
> I: why do you think (b) is right?
> *S: if she goes up at constant speed then kinetic energy does not change... that means potential energy does not change so the mechanical energy is conserved.., mechanical energy is kinetic plus potential.*
> I: What is the potential energy?
> *S: uhh... isn't it right?*
> I: why is h not changing?
> *S: (pause).. h is the height.. .1 guess h does change if she goes up the hill... hmm... maybe that means that potential energy changes. I am confused.. . .1 thought that if the kinetic energy does not change, then potential energy cannot change aren't the two supposed to compensate each other.... is it a realistic situation that she bikes up the hill at constant speed or is it just an ideal case?*

The student is convinced that the mechanical energy is conserved when the bike goes up at a constant speed and he initially thinks that both the kinetic and potential energies must remain unchanged. When he confronts the fact that the potential energy is changing, instead of reasoning that the mechanical energy must be changing if the kinetic energy is constant, he thinks that it is probably not realistic to bike up the hill at a constant speed. He wonders if it is only possible in the idealized physics world. Although he ignores the work done by the non-conservative force applied on the pedal to keep the speed constant, his statements shed light on student's epistemological beliefs about how much one can trust physics to explain the everyday phenomena. A student who chose (c) (cases (1) and (2)) provided interesting explanation: *In case (1) the kinetic energy is transferred to potential energy so the mechanical energy is conserved and in case (2)... obviously. . if the speed is constant... mechanical energy is conserved. Case (3) is out because she is accelerating.* This example shows student's inconsistent thinking. There is acceleration not only in case (3) but also in case (1) (slowing down) but the student does not worry about it in case (1). At the same time, he put cases (2) and (3) in different categories although the cyclist was pedaling in both cases.

### *Difficulty with parametric dependence of energy on variables*

Students often have difficulty in determining the dependence of various forms of energy on different parameters that can make it difficult for them to apply energy principles appropriately. Student responses to question 8 illustrate this difficulty (Singh, 2003):

8. You drop a ball from a high tower and it falls freely under the influence of gravity. Which one of the following statements is true?
   (a) The kinetic energy of the ball increases by equal amounts in equal times.
   (b) The kinetic energy of the ball increases by equal amounts over equal distances.
   (c) There is zero work done on the ball by gravity as it falls.
   (d) The work done on the ball by gravity is negative as it falls.
   (e) The total mechanical energy of the ball decreases as it falls.

Students who chose (d) for question 8 believed that the work done by gravity on the ball falling from the tower is negative. Interviews show that many students did not invoke physics principles to come to this conclusion (e.g., the basic definition of work) but thought that the work must be negative if the ball is falling in the "negative y direction". Choices (a) and (b) were chosen with the same frequency. Students who chose the correct option (b) and the incorrect option (a) both knew that the kinetic energy of the ball increases as it falls. But the former group indicated that this increase was equal over equal distances (as the ball falls the potential energy decreases by equal amount over equal distances but the total mechanical energy is conserved) while the latter group indicated it was equal in equal times. Some students who chose the correct response used the process of elimination by noting that time has nothing to do with the conservation of mechanical energy. Students who focused on speed rather than kinetic energy were likely to get confused. The following is an excerpt from an interview with a student who chose (a) and started with a correct observation but then got mislead due to faulty proportional reasoning:

I: Why do you think (a) is right?
*S: Isn't it true that the velocity of the ball increases by like 9.8 m/s every second?... .kinetic energy is (½)mv*$^2$ *(writes down the formula) so it increases by equal amount over equal time.*
I: Are you sure? Can you explain your reasoning?
*S: I am pretty sure... (referring to the formula)... v increases by equal amount over equal times.. .so v*$^2$ *increases by equal amount over equal times... mass m is not changing...*

Student response to question 9 provides another example of reasoning about which parameters influence conservation of energy.

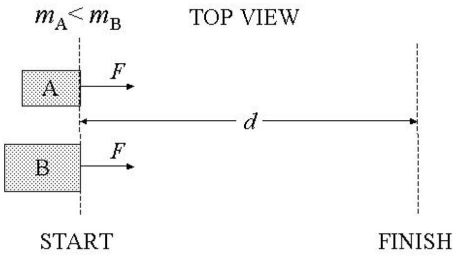


Figure 10. Two blocks are initially at rest on a frictionless horizontal surface. The mass $m_A$ of block A is less than the mass $m_B$ of block B. You apply the same constant force F and pull the blocks through the same distance d along a straight line as shown below (force F is applied for the entire distance d). Reprinted with permission from Singh (2003).

9. Which one of the following statements about Figure 10 correctly compares the kinetic energies of the blocks after you pull them the same distance d?
   (a) The kinetic energies of both blocks are identical.
   (b) The kinetic energy is greater for the smaller mass block because it achieves a larger speed.
   (c) The kinetic energy is greater for the larger mass block because of its larger mass.
   (d) Not enough information, need to know the actual mass of both blocks to compare the kinetic energies.
   (e) Not enough information, need to know the actual magnitude of force F to compare the kinetic energies.

Question 9 has previously been investigated in-depth by McDermott et al. (Lawson & McDermott, 1987). Students have great difficulty in realizing that since identical constant forces are applied over the same distance to both masses (which start from rest), their kinetic energies are identical regardless of their masses. Only 29% indicated the correct choice (a) during the post-test and the strong distracters were (b) and (c). Interestingly, many students correctly stated that the velocity of block A will be greater but they had difficulty in reasoning beyond this. Interviews show that the choice (b) was often dictated by the fact that the kinetic energy increases as the square of the speed but only linearly with mass (Lawson & McDermott, 1987).

McDermott et al. have developed and assessed tutorials (McDermott, Shaffer, & Physics Education Group, 2002) that significantly improve student understanding of energy concepts noted in the above examples.

We have developed some exploration problems that have been effective in improving student understanding of conservation of energy (Singh, 2000; Singh, 2002b). One such exploration involves loop the loop demonstration with a ball and a track that looks like a roller coaster. One side of this track goes higher than the other side. Students are asked to predict various things such as the minimum height from which the ball should be released on higher side to be able to reach the end of the track on the lower side or the minimum height from which the ball should be released so as to complete a loop without losing contact with the track. In each case, students have to explain their reasoning and invoke the principle of mechanical energy conservation.

In sum, conservation of energy is conceptually prominent in state science standards (although sometimes in quantitative form and sometimes in qualitative form), pivotal to the learning of physics, and yet very difficult for students to learn. We have identified some instructional problems that are useful for improving student learning in these areas.

### *Geometrical Optics*

Understanding of light and how it interacts with objects is important for all branches of science (Goldberg & McDermott, 1986, Goldberg & McDermott, 1987). Whether one is learning about microscopes, telescopes or human eye, one learns in geometrical optics that light travels in a straight line until it interacts with a material. After this interaction, the direction of light can change due to reflection, refraction, diffraction (which must be described by wave optics) and absorption. The Atlas of Science Literacy Project 2061 does not have a separate concept map for geometrical optics. However, according to the Atlas of Science Literacy Project 2061 “Waves” map (see Appendix C), children in grades 3-5 should be given an opportunity to learn about the basic properties of light. Helping students perform more in-depth qualitative analysis of wave phenomena in grades 6-8 can deepen this understanding. Quantitative analysis can be performed at the high school level in grades 9-12.

Geometrical and wave optics concepts (indicated in italics on the map in Appendix C) are basic to understanding a variety of phenomena pertaining to light. However, the basics of geometrical optics are surprisingly difficult even for students in college physics (Goldberg & McDermott, 1986, 1987).

The state science standards for CA, CO, RI, and WI have quite a varied treatment of optics. California and Rhode Island science standards provide the most direct reference to them, at both middle school and high school levels. Wisconsin standards (also at both middle school and high school levels) generally make reference to properties of light and models of them, which presumably must involve basic geometrical optics, although this must be inferred. Colorado science standards make the most indirect reference to this topic, with brief mention of light causing change in a system in the middle school standards, and some mention of analysis of characteristics of matter as they relate to emerging technologies such as photovoltaics.

Geometrical optics is in fact a cluster of related concepts that describe the rectilinear propagation of light in free space and its reflection and refraction when it interacts with matter (Goldberg & McDermott, 1986 and 1987; Wosilait, Heron, Shaffer, & McDermott, 1998). Teaching students about the properties of light is challenging and requires careful instructional planning. It has been documented that students have serious difficulties about the consequences of light traveling in a straight line in free space and getting reflected, refracted or absorbed after interacting with objects (Goldberg & McDermott, 1986 and 1987; Wosilait, Heron, Shaffer, & McDermott, 1998). The next three sections document the key difficulties that students have with propagation, reflection, and refraction of light.

### *Difficulty Understanding Propagation of Light Rays*

McDermott et al. (Wosilait, Heron, Shaffer, & McDermott, 1998) performed a study in which they investigated pre-service and in-service teachers and introductory physics students' understanding of light and shadow. They found that students had many common difficulties. They asked students to predict outcomes of experiments. After the prediction phase, students performed the experiments and tried to reconcile the differences between their prediction and observation.

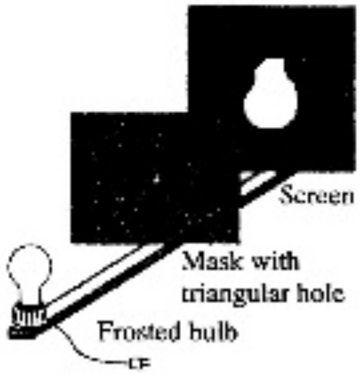
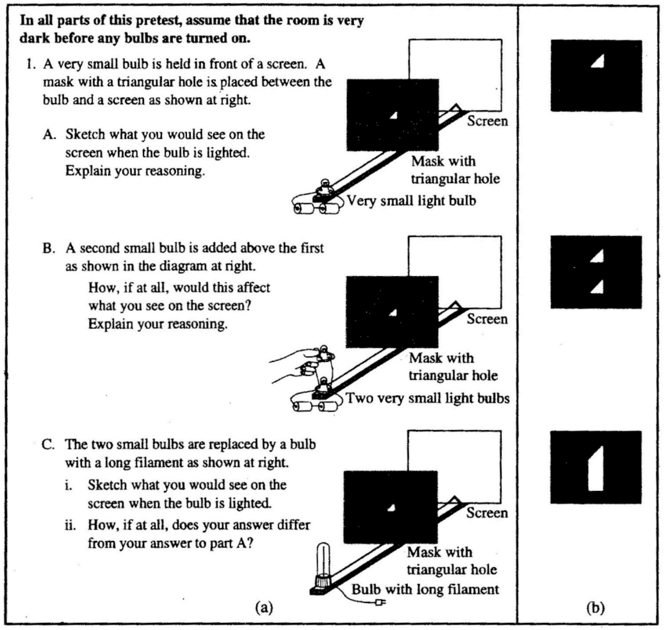


Figure 11. Experiment with frosted bulb shining through a pinhole and projecting onto a screen. Reprinted with permission from Wosilait, K., Heron, P., Shaffer , P. & McDermott, L. Development and assessment of a research-based tutorial on light and shadow. 1998, American Journal of Physics.

In one investigation (Wosilait et al., 1998), students were asked to predict what they would see on the screen when a mask with a very small triangular hole is placed between a broad extended source (a frosted bulb) and a screen (see Figure 11). This is a modified version of the classic pinhole camera setup in which a candle is placed in front of a mask with a very small circular hole and the image on the screen is an inverted candle. A very large number of students predicted that the screen will be lit only in the tiny triangular area in front of the hole in the mask. Even after performing the demonstration and observing an inverted image of the whole frosted bulb, many students could not reconcile the differences. This task turns out to be very difficult because of the way people generally interpret what it means for light to travel in a straight line (Wosilait, Heron, Shaffer, & McDermott, 1998). They do not realize that each point on the frosted bulb should be thought of as a point source of light that gives out light traveling in straight lines in all directions radially. In this study, many students seemed to believe that light can only travel horizontally through the triangular hole in the mask so that all of the light from the frosted bulb will be blocked except for the size of the hole.



**In all parts of this pretest, assume that the room is very dark before any bulbs are turned on.**

1. A very small bulb is held in front of a screen. A mask with a triangular hole is placed between the bulb and a screen as shown at right.
   - A. Sketch what you would see on the screen when the bulb is lighted. Explain your reasoning.
   - B. A second small bulb is added above the first as shown in the diagram at right. How, if at all, would this affect what you see on the screen? Explain your reasoning.
   - C. The two small bulbs are replaced by a bulb with a long filament as shown at right.
     - i. Sketch what you would see on the screen when the bulb is lighted.
     - ii. How, if at all, does your answer differ from your answer to part A?

Figure 12. Reprinted with permission from Wosilait, K., Heron, P., Shaffer , P. & McDermott, L. Development and assessment of a research-based tutorial on light and shadow. 1998, American Journal of Physics.

In another investigation, McDermott et al. (1998) changed the relative sizes of the light source and the hole through which light passed before reaching the screen. This time the source of light was a very small bulb (about the size of a Christmas tree bulb) and the triangular hole was relatively large (see Figure 12). They asked students to predict what they would observe on the screen. If one correctly uses the fact that light travels in a straight line and the hole is much larger than the size of the source, one will come to the conclusion that the image on the screen will be triangular (the same shape as the hole). The size of the triangular image on the screen will change depending on the distance of the tiny bulb from the hole. Students were also asked to predict what will happen if there were two light bulbs, one underneath another in front of the same triangular hole. In this case, the bright image on the screen should be two triangles (the lower triangular image is formed by the upper bulb and vice versa). The last task in this set was a prediction of the image formed by a bulb with a long filament in front of the same triangular hole. These tasks turned out to be extremely difficult for most students because they had never carefully thought about what it means for light to travel in a straight line (Wosilait, Heron, Shaffer, & McDermott, 1998).

To help improve understanding of light and shadow, McDermott et al. (McDermott & Physics Education Group, 1996) developed and assessed laboratory-based, inquiry-oriented curriculum for pre-college teachers. They found that instructional materials that evolved from the iterative cycle proved effective in helping students understand the implications of the linear motion of light on the formation of shadow and images. In fact, after the modified curriculum, students were able to predict the type of image formed by complicated objects under diverse situations and the effect of the change of parameters such as the distance of the object or the screen from the hole.

Singh (2000, 2002b) has developed several explorations that improve students' understanding of the concepts related to linear propagation of light and formation of images by reflection and refraction. For example, one exploration challenges students' pre-conceptions about shadows formed by obstacles including changes in the size of the shadow of the obstacle if the distance of the obstacle from the light source is increased. Another part of this exploration involves images formed by pinholes about which students have many common difficulties. These explorations have been found to be effective tools for helping students learn about rectilinear propagation of light and for developing confidence in drawing ray diagrams.

### *Difficulty with Reflection of Light*

Not only do students have difficulty in understanding the implications of the motion of light in a straight line from a source, they have difficulty understanding the formation of image by reflection of light from mirrors. Goldberg and McDermott (1986) performed a study in which they investigated student difficulties in understanding image formation by a plane mirror. The emphasis of their investigation was on examining the extent to which students connect formal concepts to real world phenomena. They found that most students can provide memorized answers to standard questions such as the image is the same distance behind the plane mirror as the object is in front. However, they cannot answer questions such as whether his/her distance from a small mirror would affect the amount he/she can see of his/her own image. Based upon interviews with many students, the researchers claim that even if traditionally taught students are given time and encouragement to reconsider, the students will most probably not even be able to draw a ray diagram that might help them answer such questions.

By gathering detailed information from interviews with a large number of students about four systematic tasks related to plane mirrors, Goldberg and McDermott (1986) were able to identify student difficulties in attempting to connect the principles of geometrical optics studied in class and the image they can see or imagine seeing in a real mirror. One difficulty that was common was the belief that an observer can see an image only if it lies along his or her line of sight to the object. Students who claimed that the object and the image were at equal distances from the mirror along the line of sight appeared not to be thinking that the mirror is a reflecting surface. In order to reconcile their experience of seeing an object shift with respect to the background, students sometimes introduced faulty parallax reasoning and predicted that an image would be in different positions for different observers.

Students also had great difficulty in deciding where, with respect to a ray diagram, the eye of an observer must be to see an image. Students often misinterpreted their past experiences. In trying to justify an incorrect prediction, students often provided reasoning that violated the law of reflection but they appeared to be unaware of it.

Students have difficulty in understanding that a person can see something only if the light reflected from that object reaches the person's eyes (McDermott & Physics Education Group, 1996; McDermott, Shaffer, & Physics Education Group, 2002). This lack of understanding makes it very difficult to understand among other things, the phases of the moon. A common misconception is that the moon is always there in the sky but is sometimes covered by the clouds which gives rise to the different shapes.

McDermott et al. (McDermott & Physics Education Group, 1996) have developed an inquiry-based curriculum for K-12 teachers that is effective in helping dispel misconceptions about the phases of the moon. The curriculum helps K-12 teachers build a coherent understanding of the reflection of light and its implication for being able to see something.

### *Difficulty with Refraction of Light*

Formation of images by refraction of light is also quite challenging for students. Goldberg and McDermott (1987) performed a study in which they investigated student understanding of the real image formed by refraction through a converging lens or reflection through concave mirror. Students were often unable to apply the concepts and principles they had learned in their college introductory physics class to an actual physical system consisting of an object, a lens or a mirror, and a screen. Many students did not seem to understand the function of the lens, mirror or screen. The study included interviews in which students predicted outcomes of experiments, performed experiments and reconciled differences.

In one part of the study, students who had obtained a real image on the screen formed by the convex lens were asked to predict what would happen if the lens was removed. Since the lens forms the image, the image on the screen will disappear if the lens is taken away. Many students claimed that the image will become a little fuzzy if the lens is removed but remain on the screen nevertheless. Others claimed that the image will not be upside down anymore without the lens and will have the same orientation as the object. Even after performing the demonstration, many students did not know how to explain the disappearance of the image.

In another part of the study (Goldberg & McDermott, 1987), students were asked to predict what would happen on the screen to the real image that is formed by refraction through a convex lens if half of the lens was covered with a mask. Since each part of the lens forms the image, the image should remain on the screen but become half as intense. A large number of students claimed that image should get cut in half if half the lens was covered. Even after observing that the whole image remains intact but the image intensity decreases, most students could not draw ray diagrams to explain it.

Singh (2000, 2002b) has developed an exploration with lenses that deals with the common incorrect assumption that covering half of a lens will cut the image in half or removing the lens will make the image fuzzy but the image will be present (in reality, if the image is formed by a lens, then removing the lens will make the image go away). Students predict what will happen in these situations and then reconcile the difference between their prediction and observation. With the help of intensity measuring device (photocell), they find that covering half the lens reduces the intensity to half but since each part of the lens forms image, the full image remains. Using the ray diagram, students try to make sense of it. Students also notice that the image vanishes when the lens is removed.

Another exploration (Singh, 2000, 2002b) deals with a model of human eye where students explore how the focal length of the eye changes in order to form a clear image on the retina. They learn about how defects in the eye prevent focal length of the eye from changing naturally to form a clear image on the retina. We have found that these explorations enhance student understanding of geometrical optics and help students build coherent knowledge structure where there is less room for misconceptions.

### *Summary*

In this paper, we have connected K-12 science standards in four states and maps of conceptual growth to research on student difficulties and research-based strategies for helping students related to three important physics concepts. These concepts are particularly important for educational interventions in the K-12 curriculum because they are pivotal on concept maps of related concepts that should be taught in the K-12 curriculum and students have many common difficulties in these areas. Since students who do not learn these concepts might have further difficulty in later learning; teachers must teach these concepts using research-based strategies keeping in mind the common difficulties students have in order to make significant progress.

These concepts are known to be extremely difficult for students and involve a variety of very robust misconceptions. Thus, learning these concepts is not a simple matter, is likely to require significant time in the curriculum, and must involve research-based curricula carefully constructed to help students build a robust knowledge structure. To aid teachers and curriculum developers in this work, we have provided an in-depth discussion of the core difficulties and some methods for challenging the alternative conceptions and helping students build a coherent knowledge structure.

One research-based strategy for helping students develop a solid grasp of these concepts discussed in this paper includes tutorials or guided inquiry-based learning modules, e.g., those developed by the University of Washington Physics Education Research group. Another strategy for helping students is to give them exploration problems that involve doing hands-on activities with guided worksheets that target common difficulties. These explorations start by asking students to predict what should happen in a particular situation, then asking them to perform the exploration and then reconcile the difference between their prediction and observation. It has been found that these research-based activities are more effective when students work on them in small groups.

Finally, we certainly do not wish to imply that other physics concepts are unimportant. However, we do wish to suggest that teachers, science education researchers, curriculum developers and those involved in the professional development of K-12 teachers and striving to improve K-12 education pay attention to the same three criteria (examining concept maps of different concept clusters, connecting these concepts to the state standards and exploring why these concepts are difficult and the research-based strategies that have been found effective in helping students in those areas) in deciding where to place emphasis on concepts to teach. For example, in some of the state standards, electricity and magnetism concepts were also prominent. It will be useful to perform a similar analysis for the electricity and magnetism concepts and connect the K-12 standards and maps of conceptual growth with the research on student difficulties and research-based strategies for helping students learn electricity and magnetism. The potential conceptual space is large, and progress should be made first on the concepts that are most important to overall student learning.

## *References*

Aguirre, J. & Erickson, G. (1984). Students' conceptions about the vector characteristics of three physics concepts, Journal of Research in Science Teaching, 21, 439-457.

Aguirre, J. M. (1988). Student preconceptions about vector kinematics. The Physics Teacher, 212.

Arons, A.B. (1990). A guide to introductory physics teaching. New York: Wiley.

Camp, C. & Clement, J. (1994) Preconceptions in mechanics: Lessons dealing with students' conceptual difficulties. Dubuque, IA: Kendall Hunt.

Champagne, A., Klopfer, L. E ., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. American Journal of Physics, 48(12), 1074.

Chi, M. T. H. (1994). Chapter 1: Thinking Aloud. In , M. van Someren, Y. Barnard, & J. Sandberg (Eds.) The think aloud method: a practical guide to modeling cognitive processes. (pp. 1-12). London; San Diego: Academic Press.

Chi, M. T. H. (1997). Quantifying qualitative analysis of verbal data: A practical guide. Journal of Learning Science, 6(3), 271.

Chi, M. T. H. Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics knowledge by experts and novices. Cognitive Science, 5, 121-152.

Chi, M.T. H. Glaser, R. & Rees, E. (1982). Expertise in problem solving. In R. J. Sternberg (Ed.). Advances in the psychology of human intelligence, Vol. 1. (pp. 7-75). Hillsdale, NJ: Lawrence Erlbaum.

Clement, J. (1983). Students' preconceptions in introductory mechanics. American Journal of Physics, 51, 352.

Fishman, B. J., Marx, R. W., Best, S., & Tal, R. T. (2003). Linking teacher and student learning to improve professional development in systemic reform. Teaching and Teacher Education, 19(6), 643-658.

Frelindich, N. (1998). From sputnik to timss: Reforms in science education make headway despite setbacks. Harvard Education Letter, 1998, 1.

Ginsberg, H. & Opper, S. (1969). Piaget's theory of intellectual development. Englewood Cliffs, N.J.: Prentice Hall.

Goldberg, F. & McDermott, L. (1986). Student difficulties in understanding image formation by a plane mirror. The Physics Teacher, November, 472-480.

Goldberg, F. & McDermott, L. (1987). An investigation of student understanding of the real image formed by a converging lens or concave mirror. American Journal of Physics, 55(2), 108-119.

Gorman, R. (1972). Discovering Piaget: A guide for teachers. Columbus, OH: Merrill.

Griffith, J. A., & Brem, S. K. (2004). Teaching evolutionary biology: Pressures, stress, and coping. Journal of Research in Science Teaching, 41(8), 791 - 809

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. American Journal of Physics, 66, 64.

Halloun, I. A. & Hestenes, D. (1985a). Common sense concepts about motion. American Journal of Physics, 53, 1056.

Halloun, I. A. & Hestenes, D. (1985b). The initial knowledge state of college physics students. American Journal of Physics, 53, 1043.

Hammer, D. & Elby, A. (2003). Tapping epistemological resources for learning physics. Journal of the Learning Sciences, 12, 53.

Helm, H. & Novak, J. (1983). Proceedings of the international seminar on misconceptions in science and mathematics. Ithaca, NY: Cornell University Department of Education.

Hestenes, D. (1995). Interpreting the Force Concept Inventory. Physics Teacher, 33, 502.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force Concept Inventory. Physics Teacher, 30, 141.

Ingersoll, R. (2003). Is there a shortage among mathematics and science teachers? Science Educator, 12, 1-9.

Kim, E. & Pak, S. J. (2002). Students do not overcome conceptual difficulties after solving 1000 traditional problems, American Journal of Physics, 70, 759.

Larkin, J. H. & Reif, F. (1979). Understanding and teaching problem solving in physics. European Journal of Science Education, 1, 191.

Larkin, J.H., McDermott, J., Simon, D. & Simon, H. (1980). Expert and novice performance in solving physics problems, Science, 208, 1335.

Lawson, R. & McDermott, L. C. (1987). Student understanding of the work-energy and impulse-momentum theorems. American Journal of Physics, 55(9), 811.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. Journal of Research in Science Teaching, 29(4), 331 – 359.

Mazur, E. (1997). Peer instruction: A user's manual. Upper Saddle River, NJ: Prentice Hall.

McCloskey, M., Caramazza, A. & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. Science, 210, 1139.

McDermott, L. C. (1984). Research on conceptual understanding in mechanics. Physics Today, 2-10, July.

McDermott, L. C. (1991). Millikan Lecture 1990: What we teach and what is learned--Closing the gap. American Journal of Physics, 59, 301.

McDermott, L. C. (1993). Guest Comment: How we teach and how students learn—A mismatch?, American Journal of Physics, 61, 295.

McDermott, L. C. & Physics Education Group, University of Washington. (1996). Physics by Inquiry, Volume 1. New York: Wiley.

McDermott, L. C., Shaffer, P. S., & Physics Education Group, University of Washington. (2002). Tutorials in introductory physics. Prentice Hall, NJ.

McDermott, L. C., Shaffer, P. S., & Somers, M. (1994). Research as a guide for teaching introductory mechanics: An illustration in the context of the Atwood's machine. American Journal of Physics, 62(1), 46.

McDermott, L. C. (2001). Oersted Medal Lecture 2001: Physics Education Research-The key to student learning, American Journal of Physics, 69, 1127.

Mestre, J. & Touger, J. (1989). Cognitive Research - What's in it for physics teachers? Physics Teacher, 27, 447.

Minstrell, J. (1992). Facets of students' knowledge & relevant instruction. In R. Duit, F. Goldberg, & H. Niedderer (Eds.), Research in physics learning: Theoretical issues and empirical studies. (pp. 110-128). Kiel, Germany: Institut Fur Padagagik der Naturwisseschaften.

Minstrell, J. (1982). Explaining the "at rest" condition of an object. Physics Teacher, 20, 10-14.

Peters, P. C. (1982). Even honors students have conceptual difficulties with physics. American Journal of Physics, 50, 501.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.

Reason, J. (1990). Human Error. Boston: Cambridge University Press.

Reif, F. (1981). Teaching problem solving-A scientific approach, The Physics Teacher, 19, 310.

Saltiel, E. & Maigrange, J. (1980). Spontaneous ways of reasoning in elementary kinematics. International Journal of Science Education, 1, 73-80.

Shugart, S., & Houshell, P. (1995). Subject matter competence and the recruitment and retention of secondary science teachers. Journal of Research in Science Teaching, 32, 63-70.

Simon, H. A. (1983). Reason in human affairs. Stanford, CA: Stanford University Press.

Simon, H. A. & Kaplan, C. (1989). Foundations of cognitive science. In M. I. Posner (Ed.), Foundations of cognitive science, (pp. 1-47). Cambridge, MA: MIT Press.

Smith, J., diSessa, A., & Roschelle, , J. (1993). Misconceptions reconceived: Constructivist analysis of knowledge in transition, Journal of Learning Science, 3, 115.

Singh, C. (2000). Exploration Center For Large Introductory Physics Courses, The Physics Teacher, 38(3), 189-190. Also, see http://www.phyast.pitt.edu/~cls/pec.

Singh, C. (2002a). When physical intuition fails, American Journal of Physics, 70, 1103.

Singh, C. (2002b). Hands-on Homework for Introductory Science. J. College Science Teaching, 32(2), 126-130.

Singh, C. (2003). Multiple-choice test of energy and momentum concepts, American Journal of Physics, 71(6), 607-617.

Singh, C. (2004). Interactive video tutorials for enhancing problem solving, reasoning, and meta-cognitive skills of introductory physics students, in Proceedings of Physics Education Research Conference, edited by Franklin, S., Cummings, K., and Marx, J., AIP Conf. Proc. No. 720, AIP, Melville, NY, 177.

Singh, C. (2007). Effect of misconceptions on transfer in problem solving, in Proceedings of the Physics Education Research Conference, edited by Hsu, L., Hendersen, C., McCullough, L., AIP Conf. Proc. No. 951, AIP, Melville, NY, 196.

Singh, C. (2008a). Assessing student expertise in introductory physics with isomorphic problems. I. Performance on nonintuitive problem pair from introductory physics, Physical Review Special Topics-Physics Education Research, 4, 010104-1.

Singh, C. (2008b). Assessing student expertise in introductory physics with isomorphic problems. II. Effect of some potential factors on problem solving and transfer, Physical Review Special Topics-Physics Education Research, 4, 010105-1.

Singh, C. (2008c). Coupling conceptual and quantitative problems to develop student expertise in introductory physics, in Proceedings of the Physics Education Research Conference, edited by Hsu, L., Hendersen, C., Sabella, M., AIP Conf. Proc. No. 1064, AIP, Melville, NY, 199.

Sokoloff, D. R. & Thornton, R. K. (1997). Using interactive lecture demonstrations to create an active learning environment. Physics Teacher, 35, 344.

Thornton, R. K. & Sokoloff, D. R. (1998). Assessing student learning of Newton's laws: The force and motion conceptual evaluation and the evaluation of active learning laboratory and lecture curricula. American Journal of Physics, 66, 338.

Trowbridge D. & McDermott, L. C. (1981). Investigation of student understanding of the concept of acceleration in one dimension. American Journal of Physics, 49(3), 242.

Tversky, A. & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. Science, 185, 1124-1131.

Van Heuvelen, A. & Zou, X. (2001). Multiple representations of work-energy processes. American Journal of Physics, 69(2), 184.

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. International Journal of Science Education, 1, 205.

Wosilait, K., Heron, P., Shaffer , P. & McDermott, L. (1998). Development and assessment of a research-based tutorial on light and shadow. American Journal of Physics, 66(10), 906-913.

Table A1

California, Colorado, Rhode Island, and Wisconsin State Standards Related to Newton's Second Law

| Level | CA<br>Science Content Standards for California Public Schools | CO<br>Colorado Model Content Standards: Science | RI<br>AAAS Project 2061: Benchmarks for Science Literacy | WI<br>Wisconsin Model Academic Standards |
|---|---|---|---|---|
| Elementary | | | Grades 3-5<br>4.F. Motion<br>Changes in speed or direction of motion are caused by forces. The greater the force is, the greater the change in motion will be. The more massive an object is, the less effect a given force will have. | |
| Middle | Grade 8 Focus on Physical Science<br>2e. Students know that when the forces on an object are unbalanced, the object will change its velocity (that is, it will speed up, slow down, or change direction).<br>2f. Students know the greater the mass of an object, the more force is needed to achieve the same rate of change in motion. | Grades 5-8<br>2.3 identifying and predicting what will change and what will remain unchanged when matter experiences an external force or energy change (for example, boiling a liquid; comparing the force, distance, and work involved in simple machines) | Grades 6-8<br>4.F. Motion<br>An unbalanced force acting on an object changes its speed or direction of motion, or both. If the force acts toward a single center, the object's path may curve into an orbit around the center. | Grades 5-8<br>D.8.5 While conducting investigations, explain the motion of objects by describing the forces acting on them |
| | Grades 9-12 Physics<br>1c. Students know how to apply the law F=ma to solve one-dimensional motion problems that involve constant forces (Newton's second law).<br>2f. Students know an unbalanced force on an object produces a change in its momentum. | Grades 9-12<br>2.3 describing and predicting …physical interactions of matter (for example, velocity, force, work, power), using word or symbolic equations | Grades 9-12<br>4. F. Motion<br>The change in motion of an object is proportional to the applied force and inversely proportional to the mass. | Grades 9-12<br>D.12.7 Qualitatively and quantitatively analyze changes in the motion of objects and the forces that act on them and represent analytical data both algebraically and graphically |

Table A2

California, Colorado, Rhode Island, and Wisconsin State Standards Related to Conservation of Energy

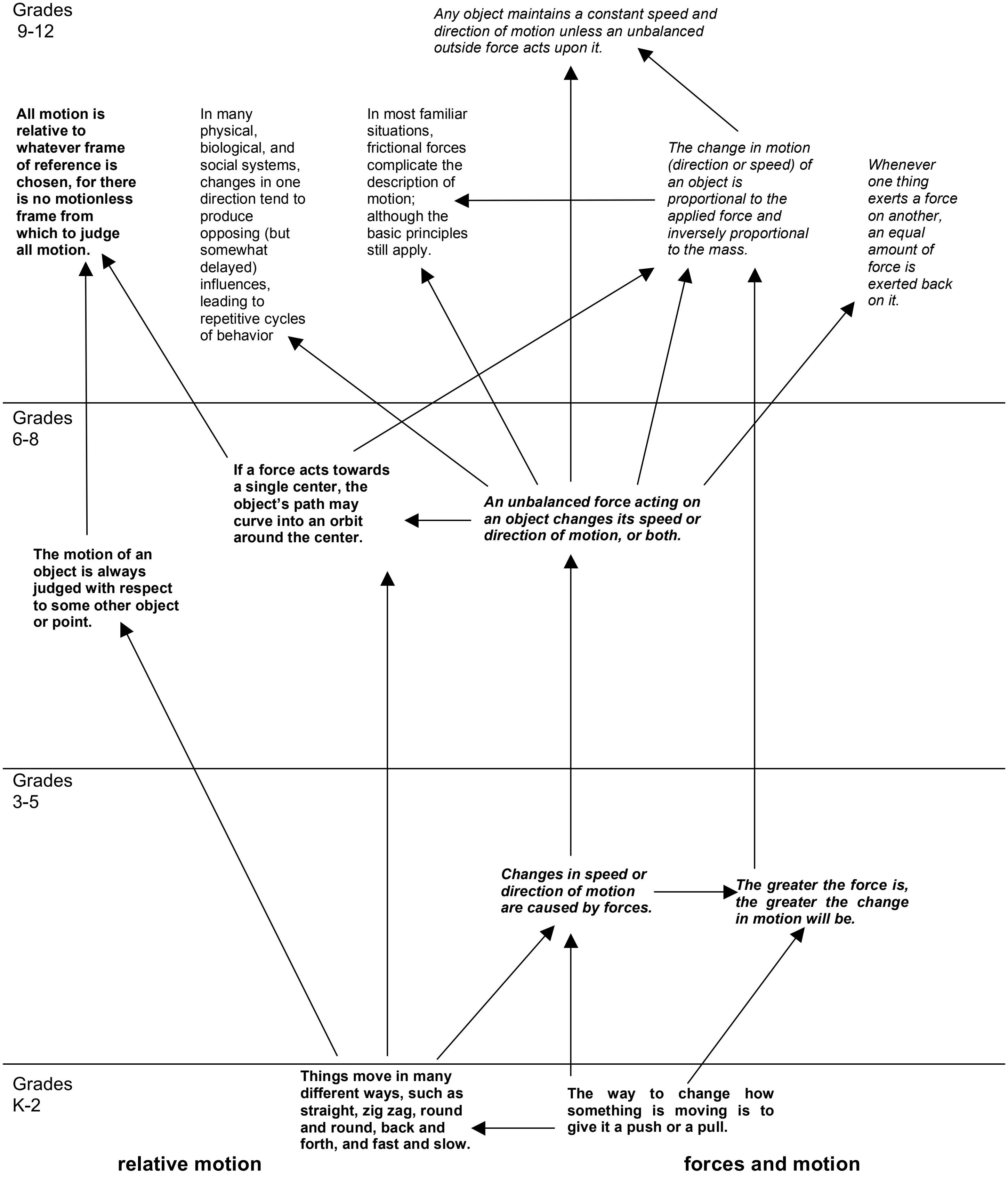
| | CA<br>Science Content Standards for California Public Schools | CO<br>Colorado Model Content Standards: Science | RI<br>AAAS Project 2061: Benchmarks for Science Literacy | WI<br>Wisconsin Model Academic Standards |
|---|---|---|---|---|
| Elementary | | | | |
| Middle | | | Grades 6-8<br>4.E. Energy Transformation<br>Energy cannot be created or destroyed, but only changed from one form into another. | Grades 5-8<br>D.8.7 While conducting investigations of common physical and chemical interactions occurring in the laboratory and the outside world, use commonly accepted definitions of energy and the idea of energy conservation |
| High | Grades 9-12 Physics<br>2. The laws of conservation of energy and momentum provide a way to predict and describe the movement of objects.<br>a. Students know how to calculate kinetic energy by using the formula $E=(1/2)mv^2$.<br>b. Students know how to calculate changes in gravitational potential energy near Earth by using the formula (change in potential energy) = mgh (h is the change in the elevation).<br>c. Students know how to solve problems involving conservation of energy in simple systems, such as falling objects.<br>e. Students know momentum is a separately conserved quantity different from energy. | Grades 9-12<br>2.2 identifying, measuring, calculating, and analyzing qualitative and quantitative relationships associated with energy transfer or energy transformation (for example, changes in temperature, velocity, potential energy, kinetic energy, conduction, convection, radiation, voltage, current).<br>2.3 observing, measuring, and calculating quantities to demonstrate conservation of matter and energy in chemical changes (for example, acid-base, precipitation, oxidation-reduction reactions), and physical interactions of matter (for example, force, work, power);<br>2.3 describing and explaining physical interactions of matter using conceptual models (for example, conservation laws of matter and energy, particle model for gaseous behavior). | Grades 9-12<br>4.E. Energy Transformation<br>Whenever the amount of energy in one place or form diminishes, the amount in other places or forms increases by the same amount. | Grades 9-12<br>D.12.10 Using the science themes, illustrate the law of conservation of energy during chemical and nuclear reactions |

Table A3

California, Colorado, Rhode Island, and Wisconsin State Standards Related to Optics

| | CA<br>Science Content Standards for California Public Schools | CO<br>Colorado Model Content Standards: Science | RI<br>AAAS Project 2061: Benchmarks for Science Literacy | WI<br>Wisconsin Model Academic Standards |
|---|---|---|---|---|
| Elementary | Grade 3<br>2. b. Students know light is reflected from mirrors and other surfaces. | | | |
| Middle | Grade 7: Focus on Life Science<br>6.f. Students know light can be reflected, refracted, transmitted, and absorbed by matter. | Grades 5-8<br>2.3 identifying and classifying factors causing change within a system (for example, force, light, heat) | Grades 6-8<br>4. F. Motion<br>Something can be "seen" when light waves emitted or reflected by it enter the eye—just as something can be "heard" when sound waves from it enter the ear.<br>Human eyes respond to only a narrow range of wavelengths of electromagnetic radiation-visible light. Differences of wavelength within that range are perceived as differences in color. | Grades 5-8<br>D.8.8 Describe and investigate the properties of light, heat, gravity, radio waves, magnetic fields, electrical fields, and sound waves as they interact with material objects in common situations |
| High | Grades 9-12 Physics<br>4f. Students know how to identify the characteristic properties of waves: interference (beats), diffraction, refraction, Doppler effect, and polarization. | Grades 9-12<br>2.3 relating their prior knowledge and understanding of properties of matter to observable characteristics of materials and emerging technologies (for example, semiconductors, superconductors, photovoltaics, ceramics) | Grades 9-12<br>4. F. Motion<br>Waves can superpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material. All these effects vary with wavelength. The energy of waves (like any form of energy) can be changed into other forms of energy. | Grades 9-12<br>D.12.9 Describe models of light, heat, and sound and through investigations describe similarities and differences in the way these energy forms behave. |

# Appendix A: Conceptual Map of Force and Motion Concepts (adapted from Project 2061 Atlas of Science Literacy)



Grades 9-12

*Any object maintains a constant speed and direction of motion unless an unbalanced outside force acts upon it.*

**All motion is relative to whatever frame of reference is chosen, for there is no motionless frame from which to judge all motion.**

In many physical, biological, and social systems, changes in one direction tend to produce opposing (but somewhat delayed) influences, leading to repetitive cycles of behavior

In most familiar situations, frictional forces complicate the description of motion; although the basic principles still apply.

*The change in motion (direction or speed) of an object is proportional to the applied force and inversely proportional to the mass.*

*Whenever one thing exerts a force on another, an equal amount of force is exerted back on it.*

Grades 6-8

**If a force acts towards a single center, the object's path may curve into an orbit around the center.**

***An unbalanced force acting on an object changes its speed or direction of motion, or both.***

**The motion of an object is always judged with respect to some other object or point.**

Grades 3-5

***Changes in speed or direction of motion are caused by forces.***

***The greater the force is, the greater the change in motion will be.***

Grades K-2

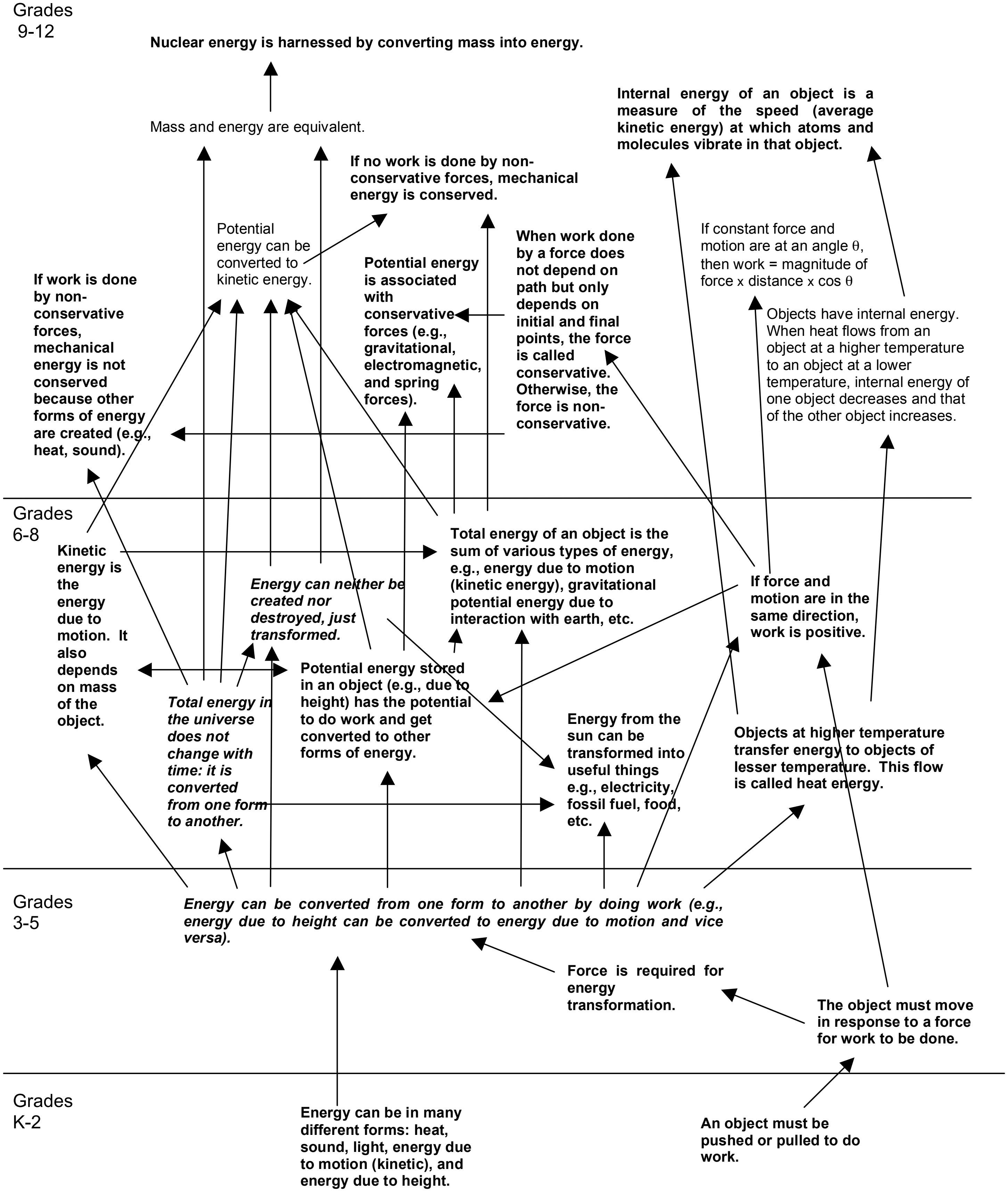
**Things move in many different ways, such as straight, zig zag, round and round, back and forth, and fast and slow.**

**The way to change how something is moving is to give it a push or a pull.**

**relative motion**

**forces and motion**

# Appendix B: Conceptual Map of Energy Concepts



Grades 9-12

**Nuclear energy is harnessed by converting mass into energy.**

Mass and energy are equivalent.

**Internal energy of an object is a measure of the speed (average kinetic energy) at which atoms and molecules vibrate in that object.**

**If no work is done by non-conservative forces, mechanical energy is conserved.**

Potential energy can be converted to kinetic energy.

**If work is done by non-conservative forces, mechanical energy is not conserved because other forms of energy are created (e.g., heat, sound).**

**Potential energy is associated with conservative forces (e.g., gravitational, electromagnetic, and spring forces).**

**When work done by a force does not depend on path but only depends on initial and final points, the force is called conservative. Otherwise, the force is non-conservative.**

If constant force and motion are at an angle θ, then work = magnitude of force x distance x cos θ

Objects have internal energy. When heat flows from an object at a higher temperature to an object at a lower temperature, internal energy of one object decreases and that of the other object increases.

Grades 6-8

**Kinetic energy is the energy due to motion. It also depends on mass of the object.**

***Energy can neither be created nor destroyed, just transformed.***

**Total energy of an object is the sum of various types of energy, e.g., energy due to motion (kinetic energy), gravitational potential energy due to interaction with earth, etc.**

**If force and motion are in the same direction, work is positive.**

***Total energy in the universe does not change with time: it is converted from one form to another.***

**Potential energy stored in an object (e.g., due to height) has the potential to do work and get converted to other forms of energy.**

**Energy from the sun can be transformed into useful things e.g., electricity, fossil fuel, food, etc.**

**Objects at higher temperature transfer energy to objects of lesser temperature. This flow is called heat energy.**

Grades 3-5

***Energy can be converted from one form to another by doing work (e.g., energy due to height can be converted to energy due to motion and vice versa).***

**Force is required for energy transformation.**

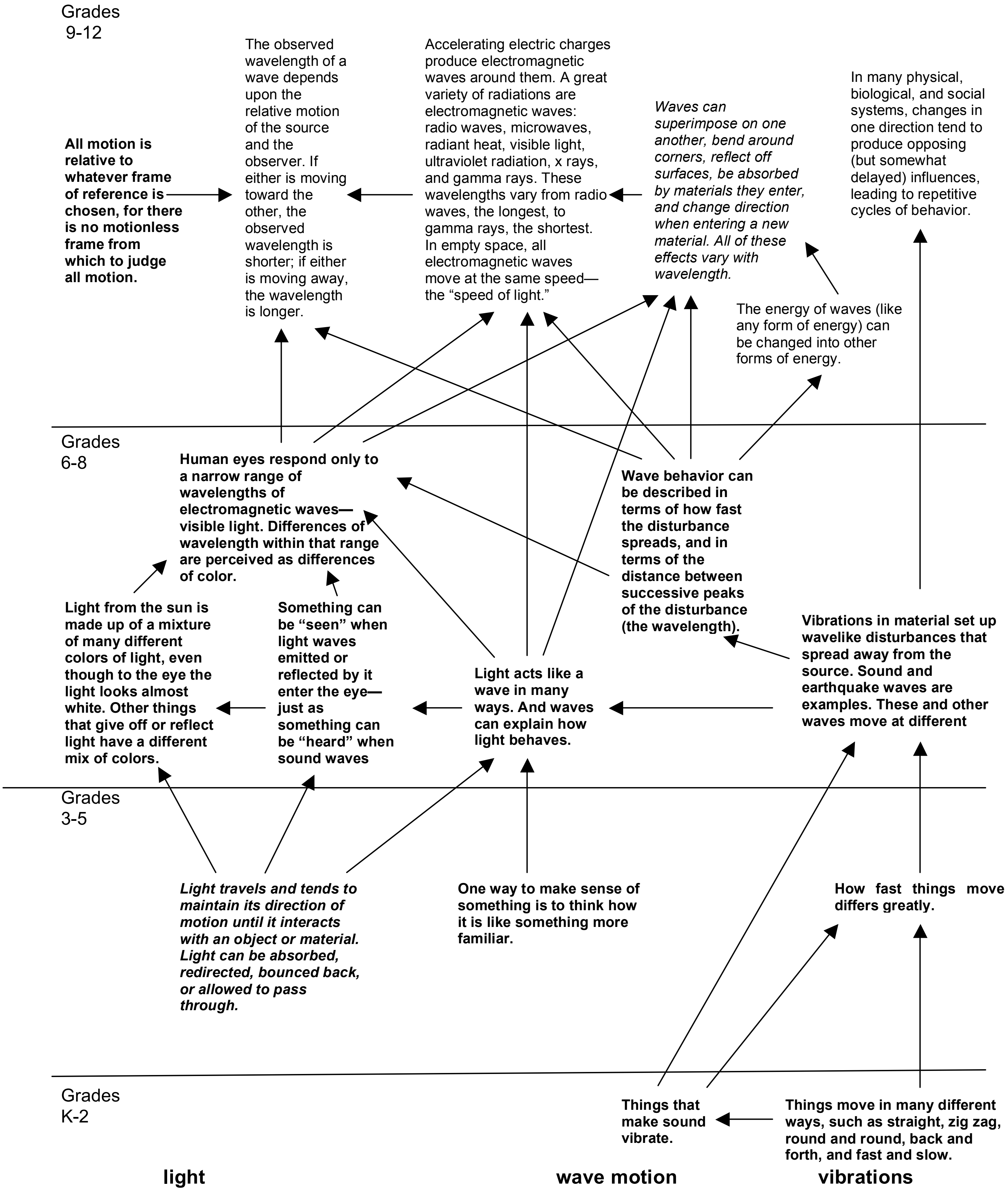
**The object must move in response to a force for work to be done.**

Grades K-2

**Energy can be in many different forms: heat, sound, light, energy due to motion (kinetic), and energy due to height.**

**An object must be pushed or pulled to do work.**

# Appendix C: Conceptual Map of Waves Concepts (adapted from Project 2061 Atlas of Science Literacy)



Grades 9-12

**All motion is relative to whatever frame of reference is chosen, for there is no motionless frame from which to judge all motion.**

The observed wavelength of a wave depends upon the relative motion of the source and the observer. If either is moving toward the other, the observed wavelength is shorter; if either is moving away, the wavelength is longer.

Accelerating electric charges produce electromagnetic waves around them. A great variety of radiations are electromagnetic waves: radio waves, microwaves, radiant heat, visible light, ultraviolet radiation, x rays, and gamma rays. These wavelengths vary from radio waves, the longest, to gamma rays, the shortest. In empty space, all electromagnetic waves move at the same speed—the "speed of light."

*Waves can superimpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material. All of these effects vary with wavelength.*

In many physical, biological, and social systems, changes in one direction tend to produce opposing (but somewhat delayed) influences, leading to repetitive cycles of behavior.

The energy of waves (like any form of energy) can be changed into other forms of energy.

Grades 6-8

**Human eyes respond only to a narrow range of wavelengths of electromagnetic waves—visible light. Differences of wavelength within that range are perceived as differences of color.**

**Wave behavior can be described in terms of how fast the disturbance spreads, and in terms of the distance between successive peaks of the disturbance (the wavelength).**

**Light from the sun is made up of a mixture of many different colors of light, even though to the eye the light looks almost white. Other things that give off or reflect light have a different mix of colors.**

**Something can be "seen" when light waves emitted or reflected by it enter the eye—just as something can be "heard" when sound waves**

**Light acts like a wave in many ways. And waves can explain how light behaves.**

**Vibrations in material set up wavelike disturbances that spread away from the source. Sound and earthquake waves are examples. These and other waves move at different**

Grades 3-5

***Light travels and tends to maintain its direction of motion until it interacts with an object or material. Light can be absorbed, redirected, bounced back, or allowed to pass through.***

**One way to make sense of something is to think how it is like something more familiar.**

**How fast things move differs greatly.**

Grades K-2

**Things that make sound vibrate.**

**Things move in many different ways, such as straight, zig zag, round and round, back and forth, and fast and slow.**

# Teaching of heat and temperature by hypothetical inquiry approach: A sample of inquiry teaching

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*Teaching science can be done using many different approaches. Hypothetical inquiry strategy is one such approach. This paper reports examples teaching of heat and temperature using the hypothetical inquiry strategy. The study was conducted as an action research project. For this purpose Wenning's (2005) 'hypothetical inquiry strategy' has been adapted. To understand the inquiry process, Kemmis and McTaggart's (2000) spiral model of action research is employed. The study suggests inquiry as an effective approach to develop students' conceptual understandings in the areas of heat and temperature.*

## Introduction

Inquiry is one of the innovative approaches of teaching and learning being used in science instruction. In the field of teaching and learning, the term inquiry mostly refers to the activities of students in which they develop knowledge and understanding of scientific ideas as well as an understanding of how scientists work (National Science Education Standards, NRC, 1996). It implies involvement that means acquiring skills and developing attitudes that permit them to seek resolutions to questions, issues and problems in line with the construction of meaningful and logical answers (Barrow, 2006).

Generally speaking, inquiry is considered a complex and difficult way of teaching science according to various accounts. Research shows that there has always been confusion over the use of inquiry in science teaching and how it can be effectively promoted in a real classroom context (Wee, Shepardson, Fast & Harbor, 2007). Regarding the effective implementation of inquiry in a classroom, Lawson (1995) suggests three crucial things: (1) teachers must understand the nature of scientific inquiry, (2) teachers must have sufficient understanding of the structure of their particular discipline, and (3) teachers must be skilled in inquiry teaching techniques.

Furthermore, questioning serves as one of the driving forces in inquiry teaching and learning. It is questioning that provokes and stimulates students to think critically. Walsh and Sattes (2005) describe the purpose of inquiry questioning in this way, "The purpose of inquiry questioning is to challenge students to think about concepts and to formulate personal responses" (p. 22). They further elaborate that while formulating our questions we need to be clear not only about the content we expect in our students to learn, but also about the kind of thinking or processes for which we will hold students responsible.

Describing the significance of teachers' awareness about different hierarchies of pedagogical practices in the inquiry process, Wenning (2005a) says, "…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" (p. 04). He proposes the following model that deals with various pedagogical practices in the inquiry process with different hierarchies based on intellectual sophistication and locus of control.

**TABLE 1** **Wenning's (2005) Model of Inquiry Processes**

| Discovery Learning | Interactive Learning | Inquiry Lesson | Guided Inquiry lab | Bounded Inquiry lab | Free Inquiry Lab | Pure Hypothetical Inquiry<br>Applied Hypothetical Inquiry |
|---|---|---|---|---|---|---|
| **Low** | | | **←Intellectual Sophistication→** | | | **High** |
| **Teacher** | | | **←Locus of Control→** | | | **Student** |

Regarding implications of inquiry in teaching and learning, research asserts that inquiry engages students in active learning by giving them the opportunity to think about the world around them. Hofsein, Shore, and Kipnis (2004) found that if designed properly, the science laboratory has the potential to play an important role in attaining cognitive skills such as scientific thinking, and it has the capacity to enable the students to understand the scientific process.

Literature presents two different approaching where students learn science. According to Westwood (2008) to some extent constructivist[1] and instructivist[2] approaches are two contrasting teaching approaches.

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[1] Constructivists believe that learner must construct knowledge from their own activities.

[2] Instructivists believe that direct teaching can be extremely effective. (Westwood, 2008).

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The former one is clearly student centered and preliminary concerned with bringing about deeper conceptual understanding and change in students. The other is more teacher-centered and concerned with effective transmission of information and skills from teacher to the learner. In literature these two approaches are also called 'progressive methods' versus 'traditional dialectic teaching'.

As action research is an important way to understand any new approach, it plays an important role for the teachers in developing their professional knowledge. Action research fosters teachers' self-improvement. It is used to enhance the capacity of teachers to serve as generators of professional knowledge in contrast to enhancing their capacity to apply someone else's knowledge (Burns, 2000). Due to its flexible nature, Kemmis and Mc Taggart's (2000) spiral model of action research is considered one of the appropriate models that most practitioners will use to improve their teaching and student learning practices. In brief, the above mentioned literature implies that it is imperative for teachers as classroom researchers to understand inquiry and its different hierarchical approaches as well as understand the role of action research in understanding inquiry as teaching approach.

### Research questions

This is study has been done to understand hypothetical inquiry approach in a real secondary physics classroom. Following was the main question and subsidiary questions of the study:

*How can I implement inquiry-teaching strategies in a physics classroom at the secondary level in a private school in Karachi?*

The following subsidiary questions have been developed to support the study:

*Q1***.** *What are the currently used teaching and learning practices of the school?*
*Q2. What are the constraints and possibilities of using inquiry as a teaching approach?*
*Q3. What are the skills required for inquiry teaching?*

### Methodology of the study

The research was conducted with 30 girl students enrolled in the 9th grade of a private secondary school in Karachi Pakistan. In this study I played multiple roles as a teacher, facilitator and researcher while the physics teacher of the class served as a 'critical friend' that gave me feedback about inquiry teaching at the end of each inquiry lesson. Multiple data collection tools were used to triangulate the study including semi-structured interviews of the physics teacher and of the focus group consisting of five students, observations of the lesson at pre intervention stage and my personal reflections that served the primary source of data collection. The purpose of the interviewing was to know the respondents' attitudes and perceptions about the inquiry teaching. I conducted semi-structured interviews with six students of the focus group and the critical friend. Following is the detail of the data collection tools and analysis of the data.

I interviewed the students together and all six participants took part in responding to my questions. Interviewing the focus group at a single time was a difficult and challenging process, because during the transcription it could create a problem to differentiate between the students' voices. But, luckily, I asked the students to state their names first and then respond to my questions. This helped me to identify students' voices during the transcription of the data. The interviews lasted for about fifty minutes. Later, the interviews were transcribed into verbatim transcripts that served as another source of data during this study.

During this study, I analyzed various documents like the textbook, the practical manual, the syllabus containing SLOs[3], the students' activities, the students' developed posters, lesson plans, the students' written reflections and the critical friend's written reflections. The document analysis served different purposes. Firstly, it informed me about the current teaching and learning practices of the school which was one of the focuses of my research questions. Secondly, it helped me understand the students' difficulty levels and the impact of inquiry teaching on students' learning, their challenges and facilitating factors, and their interest in learning the subject matter. Moreover, the poster and students' activities helped me assess the students' learning via the inquiry process. The textbook and the SLOs helped me to plan my inquiry lessons. The analysis guided me to write my personal reflections that were the prime source of data collection during this study.

Because of the nature of my study, I analyzed the data at two stages. One analysis was done during the fieldwork that was an ongoing process. At the end of each session, I analyzed field and filled notes and reflective memos that made me understand different aspects of inquiry teaching. In this way, I was able to maintain my personal reflection that served as the primary source of data as well as informed me about my next teaching session. Another stage of my data analysis was done at the end of the fieldwork that I would call 'post-data analysis'. At this stage, I had some other data in terms of students' and teachers' interviews that I later transcribed into verbatim transcripts. All data were typed on my computer and saved in a separate folder. After completing the data collection, I took printouts of the whole 45 pages of the data document and started reading them over and over until I was able to identify different themes that I coded by using colored markers. In light of my research

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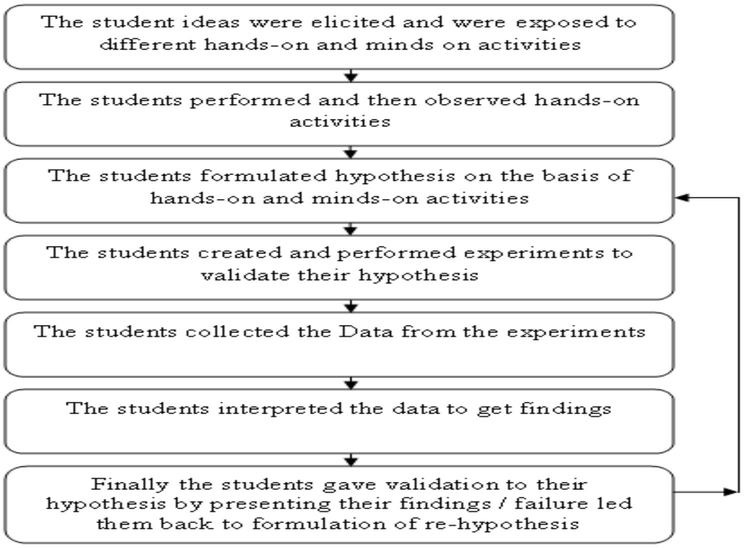
[3] SLOs stand for Students' Learning Outcomes

questions, I was able to identify three major themes that were challenges/constraints, facilitating factors, and inquiry teaching skills. Finally, I coded the data by using three different colored markers to identify sub-themes. The final stage was displaying the data to separate the sub-themes and put them under each major theme.

## Theoretical Frame Work of the Study

The study consisted of three action cycles (learning cycles). Each learning cycle consisted of three lessons; thus, there were a total of nine lessons. The study was conducted by adapting Wenning's (2005) hypothetical inquiry model as depicted in the following figure.

### Strategy of Hypothetical Inquiry Process Adapted from Wenning (2005)



The student ideas were elicited and were exposed to different hands-on and minds on activities

The students performed and then observed hands-on activities

The students formulated hypothesis on the basis of hands-on and minds-on activities

The students created and performed experiments to validate their hypothesis

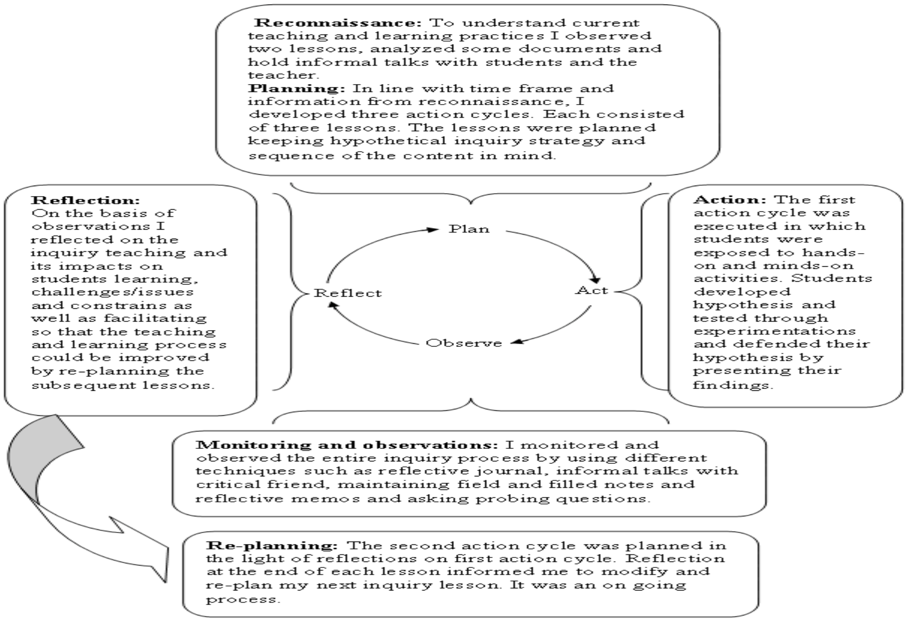
The students collected the Data from the experiments

The students interpreted the data to get findings

Finally the students gave validation to their hypothesis by presenting their findings / failure led them back to formulation of re-hypothesis

The strategy was implemented by adapting Kemmis and McTaggart's spiral model of action research (see the process in the figure below).

### Action Research Process



**Reconnaissance:** To understand current teaching and learning practices I observed two lessons, analyzed some documents and hold informal talks with students and the teacher.
**Planning:** In line with time frame and information from reconnaissance, I developed three action cycles. Each consisted of three lessons. The lessons were planned keeping hypothetical inquiry strategy and sequence of the content in mind.

**Reflection:** On the basis of observations I reflected on the inquiry teaching and its impacts on students learning, challenges/issues and constrains as well as facilitating so that the teaching and learning process could be improved by re-planning the subsequent lessons.

**Action:** The first action cycle was executed in which students were exposed to hands-on and minds-on activities. Students developed hypothesis and tested through experimentations and defended their hypothesis by presenting their findings.

**Monitoring and observations:** I monitored and observed the entire inquiry process by using different techniques such as reflective journal, informal talks with critical friend, maintaining field and filled notes and reflective memos and asking probing questions.

**Re-planning:** The second action cycle was planned in the light of reflections on first action cycle. Reflection at the end of each lesson informed me to modify and re-plan my next inquiry lesson. It was an on going process.

## Teaching Strategy

The main purpose of the inquiry lessons was to give the students conceptual and procedural understanding about different concepts related to heat and temperature. I planned to cover almost the whole chapter on 'heat and temperature' using the inquiry approach.

Pursuing the above said purpose, I systematically followed the topics starting with the differentiation of heat and temperature and ended at the last main topic of the chapter 'Specific Heat', by developing activities in a way that each successive activity progressively built the students' concepts about heat and temperature.

### First Action Cycle

The first action cycle (learning cycle) consisted of three lessons. In the first lesson, the students' ideas were elicited and they were exposed to different hands-on and minds-on activities. The purpose of the first lesson was to facilitate the students in formulating a common hypothesis so that in the subsequent classes they could validate it through experimentation. To understand the inquiry strategy, I followed the already mentioned action research model where I planned different interrelated and interconnected hands-on and minds-on activities to teach different concepts about heat and temperature. The following is the detailed description of the action cycles.

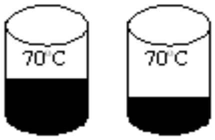
### Brainstorming and Elicitation of Students' Ideas about Heat and Temperature (10 minutes)

The first learning cycle started with the elicitation of students' ideas about heat and temperature. The purpose of elicitation was to understand students' prior conceptions about heat and temperature. Getting a lot of responses from the students, I moved to the next activity that was about the concept that 'heat' depends on the amount of matter and speed of molecules while temperature depends only on the speed of molecules. Two volunteer students were asked to demonstrate the following activity.

*Activity 1*

- Take two beakers containing different water level at same temperature shown in Figure 1.
- Put the thermometer into each beaker and record the temperature that was about 70°C

**FIGURE 1 Different Amounts of Water at Same Temperature**



Students were asked to report the temperature of the water in the two beakers. One of the two students inserted the thermometer into each beaker and found that the temperature was the same in both beakers at 70°C. The students were put into a challenging situation by asking the question "Was the amount of heat also the same in the two beakers?" This question created a kind of discrepant event[4] among the students, because the issue was that some of them thought that temperature and heat were the same concept. They responded, "temperature was the same so the heat should be" (Field notes, March, 2009). Thus, some students responded "yes" while others said "no, heat will be different in both the beakers". In this way, a debate was generated among the students. The difficulty in teaching this concept was that heat could not be measured by using the thermometer and there was no other instrument to quickly measure heat and resolve the discrepant event. Realizing that the debate could take a long time, I followed the plan and moved to the next activity.

### *Activity 2*

This activity aimed at facilitating the students to clarify the above concepts. To perform this activity, I again invited two volunteer students and led them to the following apparatus: two pairs of beakers, A and B, each containing 50ml of water at 25°C, while the other pair of beakers C and D contained water at 100ml and 40ml at same temperature of about 70°C (as shown in Figure 2). I also provided a thermometer and asked the following questions:

1. What is the temperature in the two pairs of beakers?
2. What will happen if water is poured from C to A and D to B?
3. Will the temperature rise in the beaker A and B be the same? If not, why?

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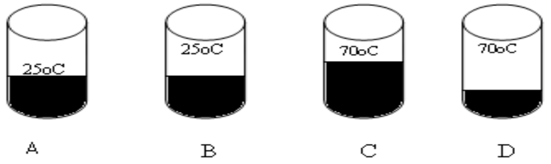
[4] Discrepant event is a situation that is counter intuitive, where something happens which goes against one's common sense.

**FIGURE 2** Heat Depends on Amount of Matter



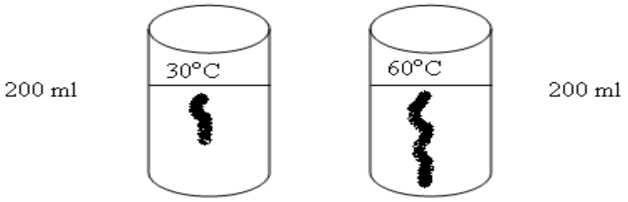
These probing questions were quite helpful, because they guided the students as well as put them into challenging situations. The first question was quite easy; the students put the thermometer into each beaker and told me the respective temperatures. The second and third questions put the students in a discrepancy because the temperature in beakers C and D were the same. Some students thought that heat would also be same. In this way, a debate was generated due to the contrasting arguments from different students. To resolve this discrepancy, I asked the two students to demonstrate the activity in front of the entire class. Very soon, they found that the temperature rise in beakers 'A' and 'B' was different. The reason explored was that a greater amount of water possesses a greater amount of heat that results in a greater rise in temperature. In this way, the discrepant event was resolved and the students developed the concept that heat depends on the amount of matter while temperature does not. From this activity, I learned that some abstract ideas such as the above can be better understood if students are involved in inquiry-based, hands-on activities. While doing these activities through demonstration, I found that some students faced scale-reading problems, where they could not read the scale correctly. The idea of inviting two students to perform the activity was good, because they helped each other to read the scale correctly. In this way, the students realized their mistakes. That was one of the causes of students' reluctance to inquiry teaching.

To give the concept that temperature depends on the speed of molecules, I demonstrated the following hands-on activity.

*Activity 3*

1. Place two beakers both containing water at 200ml but at different temperature say 30°C and 60°C.
2. I put a drop of black ink simultaneously into the two beakers and asked the students to carefully observe the activity (see Figure 3)

**FIGURE 3** Movement of Ink Droplet in Water



At the end of this activity, I asked the following probing questions:

1. What did you observe in this activity?
2. In which beaker was the speed of the ink droplet higher and why?
3. In which beaker was the speed of molecule higher?

What I observed during the monitoring was that the third question was a bit tricky and higher order thinking-oriented, because the students could not directly see the motion of the molecules; rather, they had to infer the motion of molecules from the observations of the motion of ink droplets in the two different situations. I gave the students some time to think and discuss among the other students in pairs. After about five minutes, I found that some students had developed the understanding that the speed of molecules in hot water would be higher than that in the cold water, because they inferred that the movement of the ink droplet was due to the movement of the water molecules. While reflecting on the lesson, I learned that these kinds of activities can be used to teach concepts at microscopic level such as the 'Brownian motion' (random motion of molecules) and its relationship with temperature, where it was quite visible that when temperature was increased, the random motion of molecules also increased.

At the end of the first session, I asked the students to develop a common hypothesis on the basis of their observations of the hands-on and minds-on activities and bring it to the next lesson for its empirical validations.

**Formulation of Hypothesis**

At the end of the above activities, I asked the students to develop a hypothesis about the relationship between particle speed and temperature. But the students were not able to develop a common hypothesis. The discussion with the critical friend at the end of the session informed me that the first inquiry lesson was not productive in terms of formulation of hypothesis due to different reasons. One of the students said that, "Initially we were unable to develop a hypothesis and could not understand what to do and what not to do which resulted into our frustrations and we lost interest" (S5[5], interviewed in March, 2009). What I inferred from this was that the strategy was quite new for the students and they did not have proper understanding of what a hypothesis is and how it might be formulated.

During the informal discussion with the critical friend, I explored that one cause of the students' frustration was related to the large class size. As a result, some of the students could not properly observe the activities because the activities were conducted through demonstration rather than doing it in groups. The students were not seated in groups either, they were working individually or discussing with the students next to them. That did not work effectively and resulted in students' failure to develop a common hypothesis (Field notes, 26th Jan, 2009).

*Second Lesson*

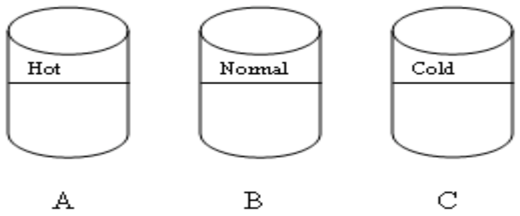
The second lesson was conducted by incorporating the emerging challenges and constraints identified during the first lesson. During this lesson, with the help of the critical friend, I divided the students into five groups each group consisted of six students, and instructed them to sit in their respective groups throughout the inquiry lessons. The second lesson was about introduction to various concepts done in the activities and linking these concepts with the students' SLOs so that a significant amount of content could be covered. The concepts included the relationship between degrees Celsius and degrees Fahrenheit; that is, how one can convert one scale into another all the while developing conceptual understanding of why and how thermometer scales were developed and what was their purpose of invention. The students also learned that a hypothesis is a tentative explanation of a phenomenon, and that a prediction is deductive process that is quite different from the inductive hypothesis development process (Wenning, 2005a)[6]. These concepts were discussed among students through generating debates led by the following probing questions:

1. What is the relationship between heat (Q) and temperature (T)?
2. How are heat and temperature measured?
3. Why was there a need for developing a different thermometer scale? What is absolute zero?
4. How can we convert $^{o}$C into $^{o}$F or vice versa?
5. How can you deduce the relationship between $^{o}$C and $^{o}$F by using a graph?

In response to the first question some students said that there was a liner relationship between heat and temperature. They provided the justification that when heat is increased temperature also increases (later they also showed the relationship on a graph). From this response, I learned that students were quite competent to use their common sense to describe a physical phenomenon. About the measurement of heat and temperature, they already knew that a thermometer measures temperature and heat is measured by a calorimeter. Moreover, they also knew the relationship between $^{o}$C and $^{o}$F, but they were unable to show the relationship on a graph. To develop conceptual understanding about the third question, the students did the following activity:

- They took three beakers A, B and C that contained hot, normal and cold water respectively (Figure 4).
- Two volunteer students came to demonstrate the activity. One student dipped her finger starting from A to B and another from C to B and shared their experience with the whole class.

**FIGURE 4 Temperature is a Relative Quantity**



The interesting thing about this activity was that, within the same group, one student was describing 'B' as cold while the other said it was warm and a kind of discrepant event was generated. Thus, there was a debate among and across the groups. To resolve this discrepant event, I provided a thermometer to the students and asked them to measure the exact temperature of the water in beaker B. Very soon the students agreed that the temperature of water in beaker B was the same. Thus, they understood that temperature is a relative quantity. Consequently, the students

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[5] S1 refers to one of the students as labeled during focus group interview.

[6] Hypothesis is a tentative explanation that can be tested thoroughly that can serve to direct further investigation, while Prediction is a statement that has no clear evidence from observations (Wenning, 2005).

realized why it was essential to develop a thermometer. But the concept of absolute zero became an issue because most of the students were not ready to accept that at absolute zero molecular energy cannot be zero. They assumed that, at absolute zero, molecular motion becomes zero so should be energy. I learned that the issue was because of the assumption that all molecular action ceases at absolute zero which is incorrect (Berg, 2008).

Reflecting on this lesson, I realized that, teaching heat and temperature through inquiry strategy was quite challenging, because these concepts were very abstract in nature and challenging to teach through hands-on activities. To give the conceptual understanding about the fifth question, I asked several probing questions such as “How will you use the two extreme points on the Celsius and Fahrenheit scale to show the relationship between them on a graph?” “How will you deduce the relationship between $^{o}$C and $^{o}$F from the graph?” For this purpose, I gave the students ten minutes to discuss among themselves in groups and represent the relationship on a graph. Initially, some of the students were confused that how to plot a graph without numerical values. Realizing the students’ confusion, first I asked the question, “What are the extreme points on both the scales (Celsius and Fahrenheit)?” Some of the students rightly shared, ‘(0$^{o}$C, 32$^{o}$F)’ and ‘(100$^{o}$C, 212$^{o}$F)’. Then I asked them to plot the graph by using these extreme points. Almost all the students plotted the following graph (Figure 5) and deduced the relationship between $^{o}$C and $^{o}$F in the following way by using the concept of slope[7] (with a little guidance).

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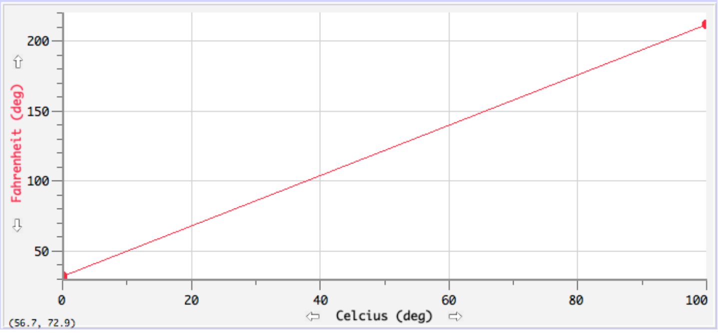
[7] Slop is the ratio between variable on Y- axis to that on X-axis.

**FIGURE 5** **Graph Between Degree Celsius and Degree Fahrenheit**



### Derivation of Relationship Between $^oC$ and $^oF$

To deduce the above relationship, the students considered the melting point of ice (0°C, 32°F) and the boiling point of water (100°C, 212°F) on both Celsius and Fahrenheit scales as shown in above Figure 5. They used the following formula of slope:

$$\text{slope}= y_2-y_1/x_2-x_1$$
$$\text{where } x_1= 0^oC$$
$$x_2 = 100^oC$$
$$\text{and } y_1= 32^oC$$
$$y_2= 212^oF$$
$$\text{slope}= (212^oF-32^oF)/(100^oC-0^oC)$$
$$\text{slope}= 180/100\ (^oF/^oC)$$
$$\text{slope}= 1.8\ (^oF/^oC)$$

Similarly they considered the melting point of ice (0°C, 32°F) and any other temperature say (°C, °F) and found the required relationship as follows:

$$y = mx + b$$

$$\boxed{{}^oF = 1.8\ {}^oC + 32}$$

The difficulty of teaching the above concept was that the topic demanded an integrated approach, where strong mathematical skills as well as a strong understanding of physics were pre-requisites to give the students conceptual and procedural understanding. During this lesson, I used different approaches in which I facilitated the students to plot a graph and also facilitated them to conduct hands-on activities. I found that the students felt quite at ease with this strategy, because they did inquiry as well as learned to link the theory with practice through generating discussions and debates (Reflective memos, 27th Jan, 2009). Regarding different inquiry processes, one student said, "Inquiry teaching was quite interesting. It enables us to see different prospective [approaches] of teaching. The classes were lively and we learned a lot" (Interviewed in March, 2009). After finishing the above activity, I asked the students to develop a common hypothesis reflecting on the hands-on activities done in the previous lesson. The students worked for making the common hypothesis that 'temperature is directly proportional to speed of molecules'. However, making a common hypothesis was challenging for the students, because they were working in groups and within the groups different students developed different statements that seemed more like predictions rather than hypothesis. Thus, there were debates within the groups as well as across the groups that continued till all the students mutually agreed on the above hypothesis. I learned that the idea of working in groups and generating discussion was fruitful, because through debate they learned that a hypothesis is a tentative explanation of a phenomenon. Meanwhile, realizing that the debate required a lot of time, I intervened and acted as a guide, sometimes as a facilitator and mentor and as a classroom teacher too. In this way, my probing questions about the students' observations of the hands-on activities helped the students reach the above-mentioned common hypothesis.

*Third Lesson*

During the first two lessons the students developed the ground for hypothetical inquiry and successfully formulated the above-mentioned hypothesis. To justify their hypothesis the students preformed the following experiment.

*Activity*

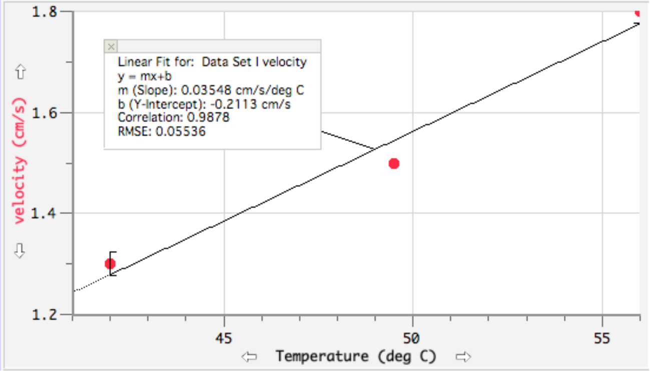
1. In their respective groups the students took a beaker containing 100ml of water at temperature say 50°C.
2. They dropped some black ink into it and by using a stopwatch recorded the time taken by the ink droplet to reach the bottom.
3. They repeated the experiment at temperatures of 60°C and 70°C while keeping the level of water the same.
4. Then the students recorded the distance covered by the ink by using a measuring tap.
5. The students calculated the speed of the ink droplet for each case and placed the value in the tabulation column (see Table 2).

**TABLE 2** **Observations**

| Obs. No. | Temperature ($^{o}$C) | Time (s) | Distance (cm) | Velocity (cm/s) |
|---|---|---|---|---|
| 1 | 56 | 2.7 | 4.9 | 1.8 |
| 2 | 49.5 | 3.6 | 5.7 | 1.5 |
| 3 | 42 | 5.2 | 7.0 | 1.3 |

6. The students plotted a graph by taking the speed of the ink droplet along y-axis and the temperature along X-axis and observed a linear relationship between them.
7. Finally, the students presented their findings (see one of the samples of work in Figure 6.)

**FIGURE 6** **Relationship Between Velocity of ink Droplet and Temperature**



During this inquiry teaching some students did not take interest and they seemed frustrated. The reason that I explored during my observations and later discussions with my critical friend was that the class was quite diversified, because some of the students were quite clear about the *basic concepts* such as scale reading and plotting a graph while others were lacking these basic concepts. For instance, some students were unable to properly read the thermometer scale, some could not use the stopwatch, and others faced difficultly in conversion units (Field notes, March, 2009). Lacking these concepts made them perform calculations incorrectly that frustrated them. They, therefore, seemed reluctant to use inquiry.

Because of lack of time only two volunteer groups presented their findings and described the graph that the speed of molecules is directly proportional to temperature (Reflective journal, March, 2009). What I felt from this lesson was that facilitating students in groups during inquiry teaching was challenging because at the same time different students demanded different things. For instance, in an activity simultaneously different students demanded fresh water, matchboxes and complained about fault in their thermometer (Field notes, March, 2009). To overcome these challenges, I adopted a number of techniques such as:

- I kept extra apparatus with me that I provided to the students on their demand.
- I frequently visited each group and asked their needs and progress.
- I asked probing questions to guide as well as put them in a challenging situation.

### *Reflection on First Teaching Cycle led to Planning for Second Action Cycle*

The second teaching cycle was planned in the light of reflection on the first teaching cycle. During the first teaching cycle I had intense informal discussions with my critical friend, and I also reflected on my field notes and personal observations so that I could understand what was good in that lesson and what was unfavorable. There were certain challenges and constraints that emerged from the first lesson that were dealt with during the second teaching episode. For example, how best students could be facilitated so that they develop an understanding of abstract ideas, and how best to manage discussions and debates as well as learning activities so that students would be able to conceptually understand the mathematical relationship between different variables and their significance in understanding physics concepts. The students' noise level was a bit high during first teaching session. To reduce this problem, prior instructions were given before the start of the second lesson. Similarly, I managed to get some extra apparatus and kept them in my possession so that whenever students needed them, I could provide accordingly. In this way, I was able to reduce students' noise level.

Moreover, during the first teaching cycle the students had developed their understandings about the inquiry process as well as their roles and the role of the teacher that helped me monitor the groups. Some students were clear enough and they did not need further guidelines to conduct their experiments, so I asked them to help the others. Because I needed a cooperative teacher to help me monitor the groups, I involved my critical friend to monitor some of the groups if I was busy with the focus group. Reflecting on various challenges, facilitating factors and necessary inquiry teaching skills, I planned my second learning cycle.

### *SECOND ACTION CYCLE*

The second cycle also consisted of three lessons. The cycle was conducted following the same pattern as was adopted for the first action cycle. In this cycle, the main concept that the students learned was 'emission and absorption of heat depends on the amount of matter'. The students performed the following activities to understand the above concept.

*Activity 1*

- They took some water (say 50ml) in a beaker and heated it for five minutes.
- They repeated the experiment for 100ml with the same initial temperature.
- They inserted a thermometer to record the respective temperature rise (which was different).

I asked the following probing questions:

1. What did you observe?
2. In which beaker was the temperature rise high and why?

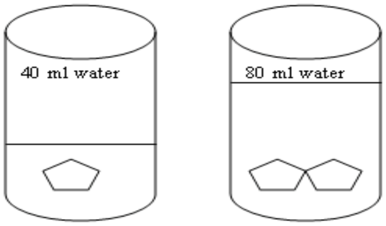
It was interesting that, almost all the groups reported that temperature rise was higher in less water. This is what our common life experience tells us, but they could not give a strong scientific argument as to why it was high. Every time during probing, I got the same response that temperature rise was more because the amount of water was less. What I learned was that this concept required explanation at microscopic level, so that the students could understand the physics behind this concept. At this stage, I realized that the issue in inquiry teaching of physics was that sometimes only relying on hands-on activities was not enough. I felt the severe need of a lecture, so that I could be able to give the students conceptual understanding by teaching them the concept of heat at microscopic level, where it says heat is the sum of all kinetic energies while temperature is the average or translational kinetic energy of the molecules. Thus, in the above activity, the greater temperature rise was because of greater translational kinetic energy of the molecules.

Similarly, to understand the concept that greater mass being associated with greater emission of heat, the students conducted following activity.

*Activity 2*

- They took two beakers containing 40ml and 80ml water (Figure 7)
- Measured the respective temperatures
- Put one small ice cube into 40ml water and two identical small ice cubes into 80ml water
- Waited for the complete melting of ice and recorded the respective temperatures.

**FIGURE 7 Melting of Ice in Water**



During this activity I asked the following questions:

1. What will happen if one ice cube is dropped into 40ml and two ice cubes into 80ml water?
2. Does the temperature fall the same in the two beakers? If not, why not?

The first question provided the students a guideline to conduct the activity while the second question put the students into a challenging situation. Some groups said the temperature fall would be different; others said it would be same. I realized that this kind of activity needed critical thinking and logical reasoning skills as well as sufficient time for discussion and debates. During the probing, some students said that the temperature would be same. I did not tell the students that their answers were right or wrong; rather, I asked how they had reached that conclusion. This strategy worked very well because the entire class was involved in the learning. Some students reflected on their previous inquiry lessons and stated that the 80ml water has more heat that caused the melting of two ice cubes, as compared to 40ml water that melted one identical ice cube and released less heat. Consequently, the temperature fall in both the water remained the same. Thus, the students learned that the greater the amount of matter, the greater would be the heat emitted. Teaching this concept through inquiry strategy was also difficult, because this required students' higher order thinking skills such as evaluation, interpretation and inferring. During probing, I found that some of the students who were lacking these skills failed to understand the concepts and I had to repeat them several times.

The problem during the learning of this concept was that most students tried to understand science on the basis of what they had experienced in their daily lives (alternate frameworks) instead of using their critical thinking and logical reasoning skills. For instance, some of the students thought that the two ice cubes would reduce the temperature more as compared to one ice cube, but they did not consider that the water was also double which did not let more temperature fall. I learned that though it was good to relate science with what one experienced in life, it sometimes causes students confusion because strange things happen in science where there is no relation between what we expect and what actually happens. Go, Cho and Paik (2007) also asserted, "Students' intuitive thinking acquired through daily life does indeed aid scientific thought. However, it can sometimes work in a counterproductive manner as well" (p. 18). The subsequent activities at some points also reflect similar notions.

At the end of these activities, I asked the students to develop a common hypothesis and the students successfully developed that 'different quantity of water exhibits different temperature rise when it is heated for same interval of time'. This time the students did not take too much time to finalize the common hypothesis. I think it was because the students concentrated more on the activities and they learned that hypothesis is actually the tentative explanation of a phenomenon.

### *Second Lesson*

The aim of the second lesson was to introduce various concepts and link these concepts with the SLOs and with the activities that the students had already done in the previous lesson. At this stage, I introduced the microscopic view of heat. The concepts were discussed through generating debates by asking following probing questions:

1. How can you differentiate between heat and temperature?
2. Can you distinguish heat and temperature by using the concept of kinetic energy?
3. Identify different topics in your textbook that can be covered by applying your understanding from inquiry teaching?

Extending the response against the first question, I was able to teach the students different definitions and interpretations of the concepts of heat and temperature. For instance, the students learned that heat is a form of energy that flows from hot to cold bodies; it is the sum of all kinetic energies of molecules of a body while temperature is the average or translational kinetic energy of molecules. Similarly, they also learned how heat transfers from one place to another place. In this way, the students were able to link the concepts with the activities and with their own SLOs. For instance, to link the concept of transfer of heat through convection, they linked it with one of the activities that they had done during the previous lessons. In this way, I was able to cover significant content through the inquiry teaching approach. I learned that teaching content through inquiry by generating discussion and debates worked very well because it boosted students' confidence and provided a basis for hypothetical inquiry (Reflection, March, 2009).

### *Third Lesson*

On the third day, the students were facilitated in testing their hypothesis. The students in five different groups were provided apparatus that included two beakers, stopwatch, thermometer, warm and tap water, burner, matchbox and tripod stand. It was a real challenge to prepare the apparatus for five different groups. For this purpose, I got help from two lab assistants and one support staff who brought the apparatus to the class and collected it when the class was finished. Throughout the inquiry teaching these two lab assistants played a pivotal role to arrange apparatus according to the provided list. There were various challenges such as different groups demanded different apparatus like some asked for help, others for fresh water and some for match boxes (Field notes, March, 2009). This created a classroom discipline problem. To overcome this problem, I asked my critical friend to help to monitor the students' learning. The noise level was reduced and students were busy in active learning. The students did the following activity:

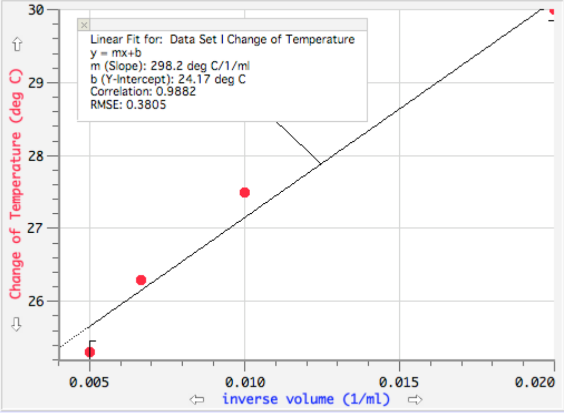
- In their respective groups the students took 50 milliliter (ml) water in a beaker at a temperature of $30^{o}$C
- Heated the water for five minutes and noted the temperature rise.
- They repeated the experiment for 100ml 150ml and 200 ml water and recorded the reading (Table 3).

**TABLE 3** **Observations**

| Obs. No. | Amount of water (ml) | Temperature Change ($^oC$) | Time (s) |
|---|---|---|---|
| 1 | 50 | 30 | 300 |
| 2 | 100 | 27.5 | 300 |
| 3 | 150 | 26.3 | 300 |
| 4 | 200 | 25.3 | 300 |

- They plotted a graph between temperature rise and quantity of water (Figure 8).
- Finally, they defended their hypothesis by presenting their findings.

**FIGURE 8** **Relationship between Amount of Water and Raise in Temperature**



```
Linear Fit for:  Data Set I Change of Temperature
y = mx+b
m (Slope): 298.2 deg C/1/ml
b (Y-Intercept): 24.17 deg C
Correlation: 0.9882
RMSE: 0.3805
```

During monitoring I observed that the idea of plotting a graph was excellent, because it gave the students multiple skills. From collecting data to analyzing and plotting a graph provided rich experience to the students, where they learned how to use scientific apparatus and how to create an experiment so as to give empirical evidence to their hypothesis. From the graph, the students described that the inverse nature of graph reveals that increase in temperature was less for greater amount of water, but conceptually, some of the students were not sound enough why there was an inversely proportionally between temperature rise and amount of water. To give the conceptual understanding, I generated a discussion and debate among the students. During the debate it was explored that a greater amount of water absorbed more heat than less water. This statement created discrepancy among the students, because both beakers of water were heated for same time. Thus, this concept also required explanation at microscopic level. I facilitated the students' reflection on their previous lesson that more temperature rise means more translational kinetic energy and less temperature means more heat absorbed by the substance that appears in different forms of kinetic energy such as kinetic energy of vibration and kinetic energy of rotation.

### *Reflection on Second Action Cycle Led to Plan the Third Action Cycle*

The third action cycle was executed keeping in view the emerging challenges and constraints as well as facilitating factors from the second action cycle. For example, the major emerging challenges included the need for a cooperative teacher for monitoring, which I fulfilled by asking my critical friend to monitor some groups. Secondly, I still needed to cover significant content. To overcome this challenge, I thought about more comprehensive activities in a way that one activity could cover several concepts. For instance, I developed an activity that covered the law of heat exchange, specific heat and heat capacity. Similarly, I also generated discussion and debates to link concepts with activities and SLOs that helped me cover significantly more content. For example, while differentiating between heat and temperature, I indirectly touched upon the caloric 'theory of heat' where heat is considered as a form of energy that flows from hot body to cold body and 'kinetic theory' which says that heat is the sum of kinetic energy of all molecules while temperature is the average kinetic energy of molecules. In this way, to a great extent, students were able to differentiate between heat and temperature. Highlighting the significance of knowing the difference between heat and temperature Einstein and Infeld cited in Niaz (2000) say, "The most fundamental concepts in description of heat phenomena are temperature and heat. It took an unbelievably long time in the history of science for these two to be distinguished, but once this distinction was made rapid progress resulted"(p.13).

*THIRD TEACHING CYCLE*

The third inquiry teaching cycle was implemented keeping the facilitating factors as well as various challenges and constraints of previous cycles in mind. It consisted of three lessons.

*First Lesson*

The lesson started with the elicitation of students' ideas about specific heat and heat capacity. The purpose of the elicitation was to know students' prior understanding, as well as to inform them about the objectives of the lesson. In groups, I provided the students a pair of beakers, a thermometer, and three different substances (piece of glass, a metallic coin, piece of some ceramic material) each with identical mass (measured by digital balance). I also provided a tripod stand, matchbox and boiling water. Aiming at giving the students conceptual understanding that different substances have different specific heat, I asked the following questions to guide the student to conduct the activity:

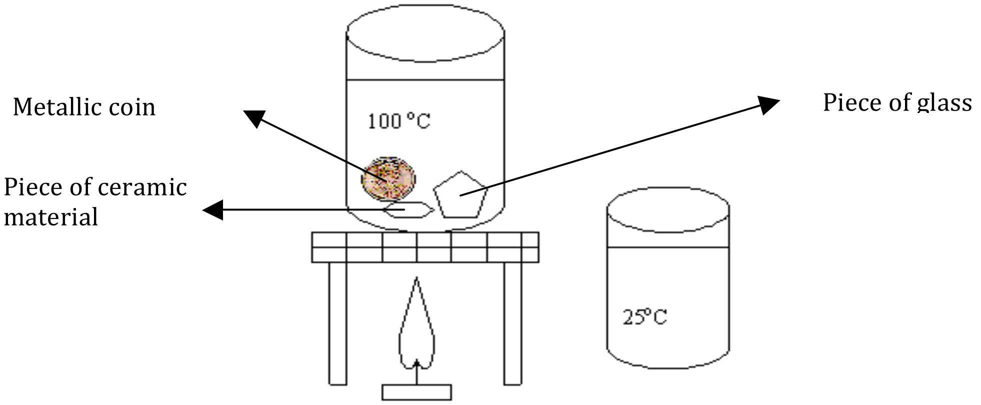
1. What will be the temperature of each object if we drop them in a beaker that contains water at100$^{o}$C?
2. What will be the effect on the temperature of a little tap water in a beaker (at 25$^{o}$C) if we transfer each object separately into it?
3. Do you experience the same temperature rise of the tap water? If not, why not?

These questions put the students into a challenging situation. In the beginning, some students said that 'ceramic' would increase the temperature more, others said the 'metallic coin' would increase the temperature more; while others said 'glass' would increase the temperature more. Still, there were some responses saying all the objects would increase the temperature the same amount. In this way, debate generated among the students. However, the students' responses were just speculations not based on concrete experience, so the debate seemed unending. I learned from this observation that teaching strategies depend on the nature of the topic and concept. I realized that the role of a teacher was how in such situations he/she leads the students towards the resolution of problems and conflicts. To end the debate, I asked the students to justify their statements experimentally and they performed the following activity.

*Activity*

- They took three different pieces of materials (a piece of glass, a metallic coin and a piece of some ceramic material)
- They put them into boiling water in a beaker (Figure 9)
- They put a thermometer into the water
- They waited till the temperature became constant (the temperature was 100$^{o}$C)
- They quickly transferred one by one the objects into another beaker containing water at 25$^{o}$C and waited till the temperature became constant
- They noted for each object the rise in temperature.

**FIGURE 9 The Three Objects that are at same Temperature**



After conducting the experiment, some of the students still reported that there was no significant change in the temperature (Field notes, March, 2009). When I asked the other groups, they reported the opposite. Then, I extended their responses by asking how they had reached the finding that there was significant increase in temperature. The students stated that they used the tap water just enough to dip the object, while the other groups had used a large amount of water that did not show considerable change in temperature (Reflective memos, March, 2009). In this way some of the groups had to repeat their experiments. From this experiment, I learned that careful monitoring and clear instruction was quite important in inquiry teaching.

Furthermore, my observations show that most of the students demonstrated procedural understanding and were quite creative but they were less concerned about different kinds of errors, such as systematic error and personal error that affected their reading (Field notes, March, 2009). I learned that as a science teacher it is imperative to make the students realize how these errors could lead them to wrong conclusions and what their consequences were. These were some of the challenges that I kept in mind during the subsequent lessons and got useful results.

On the other hand, the students were quite interested to do hands-on activities. For example, most of the students were curious to drop the objects into the hot water and observe the situations. Most of the students showed expertise in taking readings and extended help and cooperation to help those that showed inability to read the scale or did not understand concepts. At the end of these activities, I asked the students to develop a common hypothesis and the students successfully developed that 'at same temperature objects having identical mass have different specific heat'.

*Second Lesson*

The second lesson was about terms introduction. During this lesson, through discussions and debates, I covered various topics including the law of heat exchange, specific heat and heat capacity. All this activity was done by holding group discussions and debates led by the following probing questions.

1. How you can differentiate between specific heat and heat capacity?
2. How you can develop a formula for specific heat of an object?
3. What is the law of heat exchange?
4. How can the specific heat of a solid object be calculated?

During this lesson, I facilitated the students in their respective groups to calculate the specific heat of a solid bob by method of mixture. For this purpose, I provided the students apparatus that included a solid bob, a thermometer, and a beaker with boiling water, a vertical stand, a small thread and a burner. The students performed the following experiment:

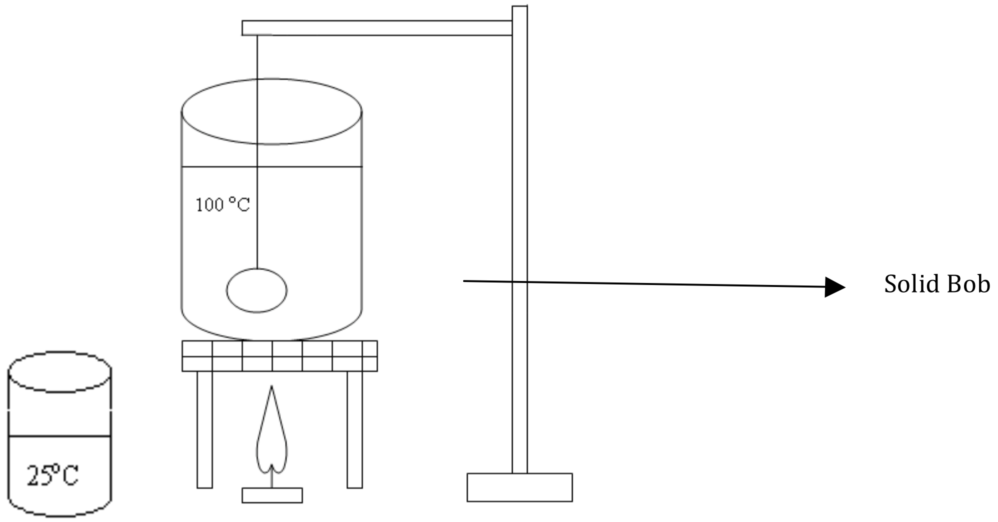
- They put the boiling water in a beaker and placed it on a table
- They put the thermometer and the bob into the water and constantly supplied heat so that temperature could remain constant (as shown in Figure 10)
- They waited till the temperature was 100°C
- They put some water into another beaker at room temperature and noted temperature as $T_2$ °C
- They quickly transferred the bob into the tap water and waited till the temperature of the mixture was constant as $T_3$ °C
- They measured the mass of the bob ($m_{bob}$) and the mass of beaker ($m_b$) and the mass of tap water ($m_w$)
- They used the following formula to calculate specific heat of the solid bob:

$m_{bob}c_{bob}\,\Delta T = m_b\, c_{bob}\Delta T + m_w c_w \Delta T$, [8]

---

[8] where $c_{bob}$ shows specific heat of bob, $c_w$= specific heat of water and $c_b$ = specific heat of beaker

**FIGURE 10 Specific Heat of a Solid Bob**



The interesting thing was that all the students were quite confident to respond to all the above-mentioned four questions, because they had almost done all the activities on the underlying concepts in the above questions. For instance, to derive the relationship ($Q= mc\Delta T$), the students reflected on the previous activities and explained that heat has a linear relationship with temperature and mass. They just needed to be facilitated to express this relationship mathematically.

During this lesson some of the students seemed frustrated (Field notes and reflective memos, 18th Feb, 2009). The reason was because some of the students could not properly calculate the mass of the solid bob, water and beaker by using digital balance. For instance, during the monitoring I observed that one group had written mass of a small solid bob as 9kg instead of 9grms. Similarly, some were unable to calculate the mass of water that they supposed to get by subtracting the mass of water from the combined mass of water and the beaker. These inabilities wasted significant time and also appeared as a challenge for me to go to each group and check whether they were taking the right reading or not. However, the idea of the mixed ability grouping introduced at the second action cycle worked significantly because the class was quite diversified. Some students were quite competent who helped the others to understand correct scale reading.

*Third Lesson:*

In this lesson, I facilitated the students to test their hypothesis. I provided the students apparatus in five groups and they performed the following experiment:

- They took a piece of glass, a metallic coin and a piece of ceramic material (all these three objects had identical mass)
- They measured the mass of each object and the of water by using digital balance
- They put them into boiling water in a beaker and constantly supplied heat
- They put a thermometer into the water
- They waited till the temperature become constant ($T_1 = 100^oC$)
- They took tap water in another beaker (at temperature $T_2 = 25^oC$)
- They quickly transferred one by one the objects into another beaker containing water and waited till temperature became constant ($T_3 = 32^oC$)
- They used the following formula to calculate specific heat of each object:

Heat lost by hot body= heat gained by cold body

- Finally, they presented their findings and defended their hypothesis.

According to my own observations and later discussing with my critical friend, I learned that there were different challenges as well as facilitating factors. For example, the biggest challenge was time management. It was really challenging for the students to get constant temperature because due to shortage of boiling water for some groups, the water took time to boil. Secondly, the students used three different things to calculate specific heat; therefore, it was difficult to do calculations for each object. The students' minor mistakes also resulted in wastage of time. For instance, one of the groups had poured out the tap water before measuring its mass. When I noticed that the students had not measured the mass, they became surprised and had to repeat the experiment from the start and that took a lot of time. The good thing I did was that I already managed the boiled water that significantly reduced wastage of time. On the other hand, there were various facilitating factors such as the collaborative and collegial attitude of students, and the students' familiarity of working in groups. Moreover, the students' interest in hands-on activities was another facilitating factor. Similarly, my own content knowledge and general pedagogical knowledge were other facilitating factors for inquiry teaching, because I was confident to ask questions and understand students' mistakes and knew how to guide them.

## MAIN FINDINGS OF THE STUDY

The purpose of this study was to understand the implementation of inquiry teaching strategies in a Physics classroom at secondary level. For this purpose, I implemented three action cycles following Kemmis and McTaggart's spiral model of action research and Wenning's hypothetical inquiry strategy. The analysis of the data revealed that there were various challenges/ constraints and issues for teaching 'heat and temperature' with the inquiry strategy. The analysis also revealed that there were some facilitating factors and skills that made inquiry teaching effective and purposeful.

### *Challenges for Using Inquiry as a Teaching Strategy*

On the basis of analysis of data, the challenges that I faced during the inquiry teaching of Physics at secondary level can be further categorized into the following sub themes.

- Teaching abstract ideas through inquiry.
- Curriculum coverage through inquiry teaching.
- Diversity of students in the classroom.
- Time, resources and classroom management.
- Motivation of students toward inquiry teaching.

### *Teaching Abstract Ideas through Inquiry*

The analysis of the data revealed that most of the content on heat and temperature was based on abstract ideas. Teaching these abstract ideas through the inquiry strategy was a challenge for me throughout the study. The core of this inquiry teaching was based on the students' conceptual and procedural understanding as well as their critical thinking skills. Throughout the teaching, it was a challenge for me to focus on the above skills through inquiry teaching. There were various concepts that demanded more time and debate as well as demanded that the students exhibit certain analytical skills such as inferring. The students had developed their hypothesis by inferring from the activities, rather than directly viewing the actual underlying phenomenon due to the natural limitations (not being able to see motion of molecules with the naked eye). The hypothesis that 'speed of molecules is directly proportional to temperature' was inferred from the motion of ink droplets in a beaker of water. Similarly, the hypothesis that 'at the same temperature objects having identical masses have different specific heat' was also inferred from another activity that has already been mentioned. What I felt challenging was that these concepts required explanations at the microscopic level. The students needed to understand the microscopic view of heat that says that heat is the sum of all kinetic energies of molecules. Similarly, the concept that the specific heat of an object depends on the composition of the molecules also required a microscopic view of heat that demanded students' high level analytical skills and more time for critical thinking (Field notes, March, 2009).

The analysis of data revealed that another issue of teaching heat and temperature by the inquiry approach was the complexity of the integration of the underlying mathematical concepts and principles and laws of physics. There were various concepts that demanded explanation not only on the basis of laws of physics, but they also required strong mathematical interpretation and justifications. The study also reveals that sometimes hands-on activities were not enough to teach abstract concepts. For example, to describe that at same temperature different objects have different specific heat, only the explanation of heat at microscopic level was not enough. It also requires mathematical calculation, so that in terms of quantity one could see the real difference between the specific heat of different objects. The problem was how to use an integrated approach in inquiry teaching to give the students conceptual understanding of physics concepts by using mathematical interpretations. For example, I learned that the derivation of the formula $Q= mc\Delta T$ at secondary level was really challenging because some of the students were not familiar with the symbols such as specific heat ($c$) and symbol of heat ($Q$). The reflection informed me that the derivation of the above formula demanded the teacher's good knowledge both in physics as well as in mathematics. Similarly, while deriving the relationship between degree Celsius and Fahrenheit from a graph by using the concept of slope was also difficult and challenging for the students. In the beginning, my probing questions about what type of relationship there was between degree Celsius and degree Fahrenheit put the students into confusion; they could not think of a linear relationship in the form of a graph. When the students were asked to find the slope from the graph and determine y-intercept, only a few students could understand, while the remaining did not understand what was meant by slope and y- intercept. Lacking these concepts, the students did not show enthusiasm in deriving the above-said relationship. Thus, what I learned from this inquiry teaching was that teaching Physics, especially those topics that involve both Physics as well as mathematical interpretation, were really challenging and sometimes it seemed an issue how these two concepts could best be taught as an integrated approach by using inquiry.

The third issue of teaching heat and temperature by inquiry approach was the students' misconceptions about heat and temperature. The study reveals that the students had various misconceptions about heat and temperature. For instance, most of the students thought heat and temperature were similar things. In a study, Calik and Kurnaz (2008) also found similar notions; they reported that for students "equal temperature means equal heat" (p.10). Similarly, some students thought at absolute zero the energy of molecules becomes zero, which is not correct. At absolute zero, molecular energy becomes minimum, but not 'zero' (Berg, 2006). Trying to answer the question in my mind, about how these misconceptions are formed, I learned that these misconceptions have different roots. Some students have developed them by their own observation while others have developed them from textbook content, because, in our context, most of the recommended textbooks (at secondary and higher secondary level) the latter notion that energy of molecules becomes zero at absolute temperature is quite visible.

Geban and Baser (2007) have also reported similar findings. They report that students have many misconceptions about heat and temperature. Everyday experience and textbooks are the basis for these concepts. Why I felt this concept was difficult to teach was because of the two different theoretical interpretations of heat; one is based on the 'caloric theory' of heat which says that heat is a form of energy that flows from hot to cold body, the other is based on the kinetic theory which says heat is the sum of the kinetic energy of molecules. Lakatos cited in Niaz (2000) reports, "Students resist the conceptual shift beyond the caloric theory, which perhaps forms part of the 'hard-core' of students' epistemological beliefs" (p. 13). Thus, one of the difficulties in teaching heat and temperature was because these misconceptions persisted strongly in students' minds and were difficult to change (Driver, 1997; Niaz, 2000). The study reveals that these kinds of misconceptions led students towards wrong calculation and resulted in students' reluctance because they had to repeat their experiments more than one time.

Another challenge for teaching concepts through inquiry was because of the issue that generally students do not take practicals seriously. In the beginning sessions, for some students the purpose of experimentation was no more than to calculate a numerical value, rather than developing their conceptual understanding out of it (Field notes, March, 2009). Describing this very nature of practicals in a Pakistani context, Halai (2003) reports in the following way,

> The context of teaching and learning in the schools is such that even these activities (practicals) are reduced to the level of rote memorization of the steps needed to complete practicals. Hence, practical work has not really helped Pakistani students develop understanding of science or understanding of doing science. (p.03)

Thus, I learned that as a science teacher, it was important to make the students realize that the purpose of doing experimentation is not only to get a numerical value, but they also need to reflect critically on how to reach a certain conclusion. In this way, I was successful in making the students realize the significance of doing experimentation. In short, the teaching of heat and temperature through inquiry strategy was challenging for me throughout the study. However, it was a good experience because it provided me an opportunity to practically understand the inquiry strategy in a physics classroom and its impacts on students' learning.

### *Curriculum Coverage through Inquiry Teaching*

In the beginning, as a novice inquirer, I was uncertain about planning an inquiry lesson and its implementation. There is always uncertainty while trying anything new and this is particularly true for the teacher researcher (Hopkins, 1996). Planning for inquiry teaching to focus on a huge content was a real challenge for me. The most difficult part for me was acting as a curriculum creator, because I had to incorporate the students' SLOs in the inquiry teaching, I had to think through many alternative ways. At this stage, I faced various challenges such as what to include and what not from the whole chapter on heat and temperature; how to plan activities so that maximum content could be covered; how the plan could be executed so that students could take maximum benefit; and how to assess students' learning outcomes. These were some of the intriguing questions that made me spend hours and hours preparing activities in a way that one activity could cover several concepts and could be finished on the allocated time. For instance, I planned an activity in which the students learned about the law of heat exchange, specific heat and heat capacity (taught in third action cycle). But what I learned was that planning in this way was so challenging, because it required huge resources in terms of equipped laboratories and other resources such as the internet.

Reflecting on the lessons, I learned that to cover the syllabus through inquiry teaching, a teacher needs to work more rigorously and needs good command on subject content. For example, to cover the given syllabus, despite being a subject specialist and having years of teaching experience, I still needed considerable time and effort to develop activities in a way that one activity could cover several concepts. Besides doing activities, I also tried to cover the interrelated topics and concepts by generating discussion and debates among the students. The good thing that I noticed was the use of episodes of lectures between inquiry teachings; because it helped the students connect the activities and the concepts with their SLOs. In this way, I was able to cover the given content. This notion is best exemplified in the comment, "First, we should discuss ideas and then we should do experiment and finally conclude with lecture connecting the theory with the practical so this will make concepts more clear" (S5, Interviewed in March, 2009).

### *Diversity of the Students in the Classroom*

The analysis of the data revealed that one of the major challenges was to focus individual students' conceptual understanding during inquiry teaching. The problem I faced in dealing with individual students' conceptual understanding was due to the diversity in the classroom. Some of the students were lacking very basic skills. My personal observations and analysis of the other data sources revealed that it was very challenging for me to focus students' basic concepts and skills such as scale reading and use of apparatus as well as dealing with conversion units and plotting a graph to show a relationship between variables. During the inquiry teaching at various points, I had to stop doing inquiry and start giving a lecture on effective use of measuring instruments and conversion units. There was a great variety in the class because some students were quite clear about these basic concepts while some others were not. Thus, it was difficult to take the entire students together, because, when I started discussing the basic concept with some students the others were left unaddressed.

Moreover, the analysis of the data also revealed that some of the students were dominating over the others, even working in groups. The informal talks with the critical friend informed me that the best way was frequently visiting the groups and make sure of the involvement of each student by asking probing questions. Commenting on this aspect the critical friend said, " They [students] differed with level, for example, in Class Nine there is a great variety. You might have noticed that some students were dominant while the others were non participative unless you ask them questions" (Interviewed in March, 2009). Reflecting on the teaching and learning, I also learned that the appropriate way was making the groups with mixed ability students, which I had done during my second teaching cycle and which significantly reduced this problem, because students helped each other and contributed to each others' learning. The following comment reflects on this perspective, "I feel that in this type of inquiry teaching we were ourselves teachers as well as students" (S2, Interviewed in March, 2009).

### *Time, Resources, and Classroom Management*

Time, resources, and classroom management were some of the major challenges during the entire inquiry teaching. I felt that my own inexperience of inquiry teaching, and being new to the context were the major reasons of difficult time and resource management. The teacher's own inexperience appears as a great problem to manage time, resource and materials in conducting inquiry teaching (Martini et al, 2004). Regarding time constraint in inquiry teaching, one student commented in this way:

> My opinion about inquiry teaching is that it was very time taking. It is true that our concepts had become clear, as we did the whole scientific study ourselves, but it took a lot of time in working out everything (S4, Interviewed in March, 2009).

The analysis of the data revealed that to manage time properly, careful attention should be given while designing and selecting the learning activities. Secondly, a teacher should be proactive to prepare and arrange the apparatus. For this purpose, I had to reach the school almost two hours earlier, so that I could arrange the apparatus and develop the activities. I first tested the activities by my own while keeping the time constraint in mind. So that, if I felt that the students would need more time to conduct the activity, I could think about alternatives. This strategy that I learned in later parts of the inquiry teaching, worked significantly to allow me to conduct the activities within the allocated time.

On the other hand, throughout the inquiry teaching, classroom management was a challenge. The analysis of the data revealed that there were various reasons for lacking classroom management. Firstly, it was because of the large classroom size. There were 30 students sited in five groups, so it was difficult to effectively monitor these five groups at a time. Classroom management is explicitly linked with student-teacher interaction (Jarrett, 1997). When I was busy with one group, the other would start raising their noise level and create disturbance in the class. Similarly, at a time different groups demanded different apparatuses and raised their voice that resulted in classroom discipline problems. Some of these challenges were overcome in the subsequent classes, but some still persisted at their lowest level till the end of the inquiry teaching. This classroom management problem sometimes seemed to affect students' participation in their learning. Regarding this aspect, the critical friend commented in this way, "You have also noticed during some activities that there was some disturbance in terms of high noise level that also caused that some students could not participate in the learning?" (Interviewed in March, 2009).

### *Motivation of Students toward Inquiry Teaching*

In the beginning, motivating students towards inquiry teaching was a real challenge. Analysis of the data revealed that I faced some kind of resistance at various points during inquiry teaching. Firstly, it was because the inquiry teaching approach was new for the students. Lacking understanding of their role as inquirers, they thought inquiry was time-consuming and difficult. One of the students said, "Because it was our first time we were not used to such type of teaching experience (S6, Interviewed in March, 2009). The critical friend also commented in the similar way, "Students were not used to this method; that is why in the beginning they did not take interest" (Interviewed in March, 2009).

In the later teaching cycles some other factors caused students' reluctance to inquiry teaching. For example, the students' lack of basic concepts and skills such as lacking the understanding of formulation of hypothesis, inability to correctly read a thermometer scale, dealing with conversion units, inability to plot a graph to show the relationship between quantities and lack of familiarity with the use of apparatus made the students frustrated. Jones, Bartley, Fazio, and Melville (2008) have also reported similar findings. They say, "Reaction to inquiry teaching ranges from students' feeling 'intimidation', 'frustration and reluctance' to students' inability to achieve good result due to lack of competence in using equipment" (p. 485). The students' views during interview also reflected a similar notion. This may be best exemplified by the statement, "Initially some of us faced problems to read scale and use apparatus and also conversion units that lacking misguided us to get wrong reading and we were frustrated" (S4, Interviewed in March, 2009). Wenning and Wenning (2006) suggest that, "If these obstacles [scale reading, interpreting data and plotting graph] could be overcome, the benefit of inquiry would be clear to our students" (p. 26). I learned that due to lacking these basic concepts/skills some of the students were unable to produce good results. Being unable to perform experiments and developing hypotheses the students showed resistance to the inquiry teaching. This notion is reflected in the following comment, "Initially we were unable to develop a hypothesis and could not understand what to do and what not to do which resulted in our frustration and we lost interest (S5, Interviewed in March, 2009).

To overcome this resistance, I took several measures. Firstly, I decided to define the role of the students and my role in this teaching approach that was crucial (Wenning, 2005b). Secondly, I used more and more interesting and relevant activities that gave the students conceptual as well procedural understanding. Describing this very nature of inquiry, one student commented by saying, "We learned procedural understanding for example, scientific method of study, handling scientific instruments and generalizing our understanding and to link it with other discipline" (S5, Interviewed in March, 2009). Thirdly, I and the critical friend involved some students to prepare a poster for a competition based on one of the tested hypotheses, which won second prize. This competition motivated students toward inquiry teaching. The critical friend commented on this aspect in this way,

> "…Another thing that I understand which created students interest was the poster competition that they have developed on the basis of one of the hypothesis that they developed and tested during your first inquiry lesson and they won prize on that" (Interviewed on 4th March, 2009).

Moreover, through discussion and debates I also tried to link activities with their SLOs that made the lesson purposeful for the students and consequently motivated them towards inquiry teaching. In this way, in the progressive lessons when the students gradually began to realize their role as self-inquirers and developed basic concepts of scale reading and the use of apparatus, by realizing that the activities were closely linked with their [school provided] SLOs, then the students took the lessons seriously. Regarding the progressive lessons one of the students said, "We came to know more about you and more about the teaching, and we came to know what to do and what not to do. And we had friendly relationship with you and with each other and that is it" (S2, interviewed in March, 2009). In the progressive lessons, the students' interest dramatically increased and they began to actively participate in the learning by interacting with each other and with the teacher. A similar notion was also reflected during the interview with the critical friend. She said, "In the later sessions, students' interaction was very good. Constantly students were helping and collaborating with each other. Not only among themselves, but they held a direct interaction with you" (Interviewed in March, 2009).

### *Facilitating Factors that made Inquiry Teaching Effective and Purposeful*

The analysis of the data revealed that because of the school culture and rich resources, there were certain factors that facilitated my inquiry teaching. Some of the major facilitating factors included: variety of hands-on activities, support from lab assistance and support staff, infrastructure of the classroom, facilitator as critical friend and cooperative teacher, time duration and availability of resources, students' familiarity with group work and cooperative learning and my own content knowledge and understanding of the curriculum.

Analysis of the data revealed that there was a strong relationship between preparing hands-on activities, my own in-depth understanding of the content knowledge, and understanding of the curriculum of the private examination Board. I realized that the privilege of my command on content knowledge and understanding of the curriculum facilitated me by preparing appropriate interrelated and interconnected hands-on and minds-on activities. The informal discussions with the critical friend and later interviews with the students also reflected that the activities were quite comprehensive, in the sense that they provided the students conceptual understanding and enabled them to cover significant content on heat and temperature. Moreover, the variety of the hands-on and minds-on activities put the students in a comfortable position where they felt at ease to make common hypotheses. Describing this aspect of inquiry teaching one student said, "In my opinion, I think we made observations from experiment that was the main thing that helped us to develop the hypothesis and prove them through experimentations and practicals" (S3, Interviewed in March, 2009).

Moreover, the reflection on the inquiry teaching informs me that because of my content knowledge, I was quite able to intervene at the time that they got stuck. Whenever I perceived that the students were stuck, I intervened by asking probing questions. My content knowledge helped me to rightly direct the students towards their aims. Moreover, the understanding of the curriculum enabled me to design students' learning activities according to their contextual needs and interests. Consequently, it enabled me to gain the students' interest, as well as enabled me to cover significant content from the chapter on heat and temperature. I realized that without content, it would not be effective.

Furthermore, the school was one of the "good" schools, so another facilitating factor during this inquiry teaching was support from the two lab assistants and support staff. The lab assistant helped me to prepare apparatus according to my checklist, while the support staff helped me in preparing things like boiling water and ice cubes and also took the responsibility of bringing the apparatus to the classroom and collected them at the end, so that I could maintain security and protection to the students as well as to the apparatus. This was one of the great privileges that I explored during my reconnaissance stage and requested the critical friend to ask the lab assistants and support staff for their cooperation, which was quite appreciable. This facility may not be available in other contexts that consequently add another challenge for the teacher.

The analysis of the data revealed that the physical infrastructure of the classroom was quite appropriate for inquiry teaching, because there was enough space and the chairs and the tables were light and quite flexible. Whenever I wanted to change the position of the students I did not get any difficulty. Moreover, the time for each inquiry period was eighty minutes and three days in a week. Though it was not sufficient, but to a great extent I was able to conduct the inquiry quite successfully.

Moreover, the analysis of the data revealed that the most significant part of the inquiry teaching was its activity-based teaching approach. All the students appreciated the activities. On this aspect, one of the students commented in these words, "Mostly we study theory in our routine classes but here it was learning with fun by doing activities" (S1, Interviewed in March, 2009). The availability of different varieties of apparatuses enabled me to think in many alternative ways to design more interesting and comprehensive learning activities. Many times the students complained to change the thermometer and stopwatches, and because of availability of apparatuses I saved a lot of time by catering to the students' needs and had no difficulty in doing so.

Furthermore, analysis of the data revealed that the availability of the critical friend during the inquiry teaching was quite effective and fruitful. Firstly, because the critical friend was more experienced and knew the context of her students. Therefore, her presence in the classroom helped me maintain classroom discipline. Secondly, from time to time, I had informal talks with her and got her feedback about different aspects of my teaching practices. In this way, she not only gave me feedback, but also significantly contributed during monitoring and provided me support to access the Physics laboratory and other resources like the library and internet. Thirdly, she was quite cooperative because she accepted my request to teach in alternative weeks, because during the off weeks I wanted to reflect on my previous cycle and re-plan my next inquiry lesson. In this way, the one week break was enough for me to think and prepare interesting and relevant learning activities, so that I could motivate students towards inquiry teaching and also give them conceptual and procedural understanding as well as critical thinking skills. In brief, this facility made my inquiry teaching more effective and purposeful.

The analysis of the data revealed that because of the nature of the context, the students were already familiar with group work and cooperative learning strategies; thus, giving tasks in groups was not a new thing for the students. This familiarity helped me maintain good coordination within groups as well as across the groups. Because of the nature of the study, it was necessary that there should be good coordination among the groups. Thus, I did not take a lot of time to guide the students about working in groups and even about cooperative learning. Consequently, the students saved a lot of time.

### *Skills for Effective Inquiry Teaching*

During the study, I realized that there were some skills that were quite effective in the inquiry processes. Some of the significant skills that I explored were: strategy of multiple approaches to teaching, understanding of different hierarchical approaches in inquiry teaching and general pedagogical knowledge.

During this study at various points, I realized the need of multiple approaches to teaching. Because of the nature of the context, I needed to focus on students' SLOs and the given content. Thus, it was essential to switch to different approaches of teaching such as group discussion and debates and bits of lecture, so that the students could be guided to link the performed activities with their specific needs. In this way, the learning was purposeful and gave real benefit to the students (Field notes, March, 2009). During discussions with the critical friend, as well as during interviews with the students, it was realized that there should be activities as well as bits of lecture so that practical can be linked with theory to enable the students to generalize their learning.

Moreover, the reflection on the inquiry lessons made me realize that only using the hypothetical inquiry process was not enough to teach complex concepts. I felt that to teach physics well by inquiry approach, a teacher should know different hierarchal approaches of inquiry processes such as interactive demonstrations (Wenning, 2005a). Reflecting on this very notion, Wenning (2005a) says, "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" (p.04). The analysis of the data informed me that the best way in inquiry teaching was taking gradual and step-by-step progression. I realized that there should be a step-by-step progression in the use of inquiry no matter how talented the student may be. Because of my literature review, I had good understanding about the hierarchy of different inquiry processes. Thus during inquiry teaching, I understood that hypothetical inquiry falls at a higher level of intellectual sophistication as compared to inquiry lab (Wenning, 2005a). So, I realized that before directly embarking students on hypothetical inquiry, it was more effective to start from basic inquiry process, such as demonstrative inquiry through hands-on activities, so that students could gradually understand the inquiry process and construct their learning in a step by step basis rather than directly jumping into high level critical thinking skills which in my case (in the initial lesson) made the students confused and frustrated. In the later sessions, I adopted the above approach, where I decided to lead the students forward from simple hands-on activities in which I used many questions and then some specific questions. This basic inquiry approach provided the students a basis to move towards a high level hypothetical inquiry approach, where the students were more independent to develop their hypothesis and its testing. In this way, what I experienced was that the students not only learned concepts by constructing their knowledge but they also enjoyed the journey of procedural understanding in inquiry process. The critical friend's comments provide evidence for this notion: "The approach you used was mostly based on activity-based learning in which the students took great interest and developed various concepts. The teaching was effective in this sense; it was not based on rote learning" (Interviewed in March, 2009).

Another important teaching skill I learned was 'the teacher as a reflective practitioner'. During the entire teaching, I continuously reflected on my own teaching and learning practices. In this way I was able to identify the strengths and weaknesses of my teaching practices. The incorporation of these weaknesses and strengths in the subsequent lessons made the inquiry teaching more effective and purposeful. Moreover, these critical reflections made me able to understand different aspects of inquiry teaching and ways to improve them, so that I would be able to develop students' conceptual and procedural understanding as well as their critical thinking skills.

## REFERENCES

Barrow, H.L. (2006). A brief history of inquiry: From Dewey to Standards. *Journal of Science Teacher Education, 17, 265-278.*

Berg, K.C. (2008). The concepts of heat and temperature: The problem of deterring the content for the construction of an historical case study which is sensitive to nature of science issues and teaching –learning issues. *Science and Education,* 17,75-114.

Burns, R. B. (2000). *Introduction to research methodology* (4th ed.). London: Longman.

Calik, M. & Kurnaz, M.A. (2008). Using different conceptual change methods embedded within the 5E Model: A sample teaching for heat and temperature. *Journal of Physics Teacher Education Online*, *5*(1), 3-10.

Dean, L.B. (2006). Quality in education. Teaching and leadership in challenging times. Karachi: *An International Conference at Aga Khan University Institute for Educational Development, 1*, 129-153.

Go, Y.M., Cho, B.K. & Paik, S.H. (2007). Korean 4-to 11 – years-Old students conceptions on heat and temperature. *Journal of Research in Science Teaching*, *44*(2), 284-302.

Halai, N. (2007). Curriculum reforms in science education in Pakistan. In R.coll, education in the context: *An international perspective of the implementation and the students experienced curriculum*. Netherlands: Sense Publishers.

Hofstein, A., Shore, R. & Kipnis, M. (2004). Providing high school chemistry students with opportunities to develop learning skills in an inquiry type laboratory: a case study. *International Journal of Science Education, 26*(1), 47-62.

Hopkins, D. (1996). *A teacher's guide to classroom research* (2nd ed.). Philadelphia: Open University Press.

Jones, D., Bartley, A., Fazio, X. & Melville, W.( 2008). Experience and Reflection: Pre-service science teacher's capacity for teaching inquiry. *Journal of Teacher Education*, *19,* 477-494.

Kemmis, K. & McTaggart, R. (2000). Participatory action research ( pp 595-600). In N. K. Denzin & Y. S. Lincoln, (Eds.), *Handbook of qualitative research* (2nd ed.). London: Sage Publication, Inc.

Koshy,V. (2005). *Action research for improving practice: A practical guide*. London: Paul Champman Publishing.

Martini, M., Otaala, J., Mc Donald, J., Hubbard, D.P., Abell, K.S & Jr, N.J.W. (2004).

Dilemmas of teaching Inquiry in elementary science methods. *Journal of Science Teacher Education, 15*(4), 257-279.

National Research Council (NRC). (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Science Council. (2000). *Inquiry and the National Science Education Standards*. Washington, DC: National Academic Press. Available http://www.nap.edu/books/0309064767/html/.

Niaz, M. (2000). A framework to understand students' differentiation between heat energy and temperature and its education implications. *Interchange, 3*(1), 1-20. Netherlands: Kluwer Academic Publishers.

Wash, A.J. & Sattes, D.B. (2005). *Quality questioning: Research based practice to engage every learner*. London: Sage Publication Ltd.

Wee, B., Shepardson, D., Fast, J. & Harbor, J. (2007). Teaching and learning about inquiry: insights and challenges in professional development. *Journal of science teacher education, 18,* 63-89.

Wenning, C.J. (2005a). Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes. *Journal of Physics Teacher Education Online, 2*(3), 3-11.

Wenning, C.J. (2005b). Minimizing resistance to inquiry-oriented instruction: The importance of climate setting. *Journal of Physics Teacher Education Online*, *3(2),* 10-15. Available: http://phy.istu.edu/publications/minimizing resistance.pdf

Westwood, P. (2008). What teachers need to know about teaching methods. Australia: Acer Press.