Teaching to Promote Deep Understanding and Instigate Conceptual Change

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ABSTRACT

This paper focuses on (1) how to promote deep understanding by making the students to question their inherent conceptual knowledge of how the world works, and (2) on how to correct these views should they be different form the scientifically proven views. This paper also reviews alternate methods of teaching that promote real learning, and explains what it entails to provoke deep understanding and conceptual change. This paper suggests an additional method of how the teacher can promote deep understanding that works best in small classes and in group situations. The teacher, first, has to select a hook that will engage the students and will make them want to know more. The next step is to help the students assimilate and accommodate the new information. This can be done by asking the right questions at the right time and provoking the students to dig more deeply into the problem at hand. Making meaningful associations and suggesting how to chunk the new information might help. In cases, when students come to class with an erroneous conceptual understanding of the world around them, a more radical approach is needed to change student's prior beliefs. They need to be confronted with their personal beliefs, realize that these are not working to solve the problem, and be led through constructing a scientifically more correct model. What is important throughout the learning process of the students', is that they really think through all arguments on their "own" and "construct" further knowledge upon already understood concepts. A good instructor can further prompt the students to construct a mental model, instigate them to reflect on their own thinking, and finally provide good examples of how to transfer the knowledge to other situations. The ultimate goal is to promote deep learning in the students' own minds.

1. Introduction

1.1. Historical Background

Education research has shown repeatedly that what we teach and what students actually learn can be remarkably different. This area of research, of understanding of how people learn, was pioneered by Jean Piaget (Piaget 1952, 1973a, b, 1977, 1978) and Lev Vygotsky (Vygotsky 1962, 1978), and builds on earlier findings of the Gestalt School of Psychology (Wertheimer 1912, 1938, Koffka 1935, Köhler 1940). In the late 50's, the field of cognitive sciences emerged out of multidisciplinary studies among philosophy, developmental psychology, computer science, neuroscience, and several branches of psychology. Over the past 25 years, further studies among cognitive scientists and educators have then yielded yet new knowledge about the nature of teaching and learning (see Bransford, Brown, & Cocking 2000 for an extensive review and list of references). These advancements of science educators and cognitive scientists have also inspired a few professional scientists (Arons 1990, McDermott 1984, 1991, and Reif & Heller 1982) to become interested in educational issues (for overviews on physics education research see McDermott & Redish 1999, Aarons 1999, Redish 2003, and Knight 2004). Like others before them, physicists (e.g., Hake 1998) then verified that the teaching-by-telling method is indeed the most inefficient method teaching physics. Furthermore, science educators are now realizing that what we teach and what students learn are actually two different things (e.g. Mazur 1992). It turns out that many students are still holding the same misconceptions that they had prior to teaching (e.g. Schneps and Sadler 1998). Despite being able to solve advanced problems, students often fail to comprehend the most basic concepts (e.g. Mazur 1997). Currently, a small group of physicists and physics education researchers are studying how students learn select physics concepts (e.g., various talks presented at latest physics education research conference by Wittmann, Heron, & Scherr, 2005). What is needed now, are more collaborative studies between educators, cognitive scientists, and content specialists (professional scientists), that focus on the details of how students really learn concepts, how they construct knowledge, and how they make sense of the world in which they live.

1.2. What are "Concepts"?

Concepts are like mental representations which, in their simplest forms, can be expressed by a single word, such as "plant" or "animal", "alive" or "dead", "table" or "chair", "apple" or "orange" (e.g. Carey 2000). Concepts may also represent a set of ideas that can be described with a few words. Through the use of language, individual concepts can be connected to build more complex representational structures, such as "babies crawl" or "birds fly". At other times, two concepts can be combined to form a third representational structure. An example of the latter could be "density", which is the "matter" per "volume", i.e., a concept that stands alone, but is a product of two other concepts. Through the use of language, we can thus create new concepts that can stand by themselves. More complex concepts can describe a whole idea, such as "the Theory of Natural Selection". Similarly, through the use of math, we can build somewhat more abstract theories that in the end up representing one idea, like for example "the Big Bang

Model of the Universe". In other words, within a particular representational structure, concepts help us to make deductions and explain even more complex ideas. Concepts can thus act as building blocks of more complex or even abstract representations.

1.3. What is "Deep Understanding"?

In the cognitive sciences the term "deep understanding" generally refers to how concepts are "represented" in the student's mind, and most importantly, how these concepts are "connected" with each other (Grotzer 1999). Representations are generally made in the form of images (and sometimes sounds or smells) in simple cases, and in the forms of models in more abstract situations. Deep understanding then means that the concepts are well represented and well connected. As such, deep understanding of a subject involves the ability to recall many connected concepts at once, where every single concept has a deep meaning in itself. Deep thinking then involves being able to make further connections between the webs of concepts. Deep thinking involves the construction of new concepts and is almost always based on what the student already knows. Thus it is also very important to assure that the most basic concepts are profoundly understood and well connected. Constructing successive arguments on somewhat shaky knowledge results in not-so-well connected further concepts. This then gives the learner the feeling of having a somewhat superficial understanding. Not seeing the connections between interrelated concepts leaves the learner with a feeling of mindless thinking. When a learner "makes sense" of new material he is able to make the connections between different concepts.

An expert in a particular field does not just have more knowledge, but the knowledge he has is connected in a logical and meaningful manner. This is important because when individual facts are recalled it is as if a whole set of interconnected further concepts are accessed at the same time and whole sets of (neural) networks become activated. An expert does not just have a much better overview of the field, but he sees all the connections between various concepts. Another big difference between how experts and novices learn is in how they "chunk" information. An expert has a much better overview over the whole subject, i.e., he sees the connections between the concepts. The human brain seems to be limited to how many facts it can remember, however when many facts are chunked together into meaningful concepts or networks of concepts, the amount of material to remember appears to be relatively less. Associations are helpful in remembering facts, and the more meaningful the associations are the easier it will be to recall the big picture of what is really going on.

1.4. Why Care About Teaching for Conceptual Change?

It is generally accepted that students do not enter the classroom as a "blank slate" (see Pinker 2003 and earlier references therein). They often come to school with already formed ideas on many topics, including how they view and interpret the world around themselves. These views (as reviewed in more detail in section 2.4) can sometimes be quite elaborate and well thought through. However in sometimes students might not yet have a pre-existing view. In those cases, they will nevertheless try to make meaning of the situation, often instantaneously, by making associations to somewhat related previous ideas and experiences (see also Zirbel 2005). The main point is that the initial or newly created world views almost always have a base to them. In some cases these views may be emotionally loaded and might have even been well thought through to some extent. Therefore it is no surprise that, regardless of their content, these views will be highly resistant to change. Science education researchers (see section 2.4) have found further, that individuals whose ideas conflict with new information might disregard the new information in favor of their existing beliefs. In extreme cases they might even defend their prior beliefs.

1.5. Why is Conceptual Change so difficult?

Understanding of how students learn and form their concepts in the first place is a topic that is researched extensively in Science Education Literature. It requires that we have some understanding of how our brain works, how we think, and how we build up upon prior ideas – in short it requires some understanding of how we learn. At the biological level, learning is a process that has been occurring ever since the first formation of the brain cells during the embryonic stage and will continue until death. Information is stored in various locations in the brain which consists of a rather elaborate network of neurons that communicate with each other (see for example, Damasio 1999, Spitzer 2002, LeDoux 2003). This network has been established through prior sensory, emotional, and intellectual experiences, even to the degree that we have learned which stimuli to perceive or ignore. Specific patterns have been established and have even become somewhat hardwired. Whenever we experience something new, the brain searches for an existing network into which to fit that information, and if that network exists, we can process and evaluate the information relatively quickly and at ease. But if we are asked to learn a new skill, additional connections among the neurons have to be made – which almost always takes some time, effort, and experience. The same is applicable to the process of thinking where old and new information is combined and evaluated, and, if need be, new circuits might be established. Thus thinking in ways we have already learned will be much easier than being challenged to think in new ways. Since the process of evaluation of signals involves the thalamus, the brain's emotional processing center, the conclusions we reach will also have an emotional component (e.g. LeDoux 1999). The formation of concepts or belief systems is thus a rather personal and grounded experience that requires considerable effort. The good news is that new behavior patterns and new concepts can be learned, but it does require work (as does creating new networks and changing the hardwiring). In other words, new concepts cannot be adopted, they have to be fitted into existing networks and go through all the emotional filtering and evaluation processes first. And even if a newly taught concept might sound logical, it can only be employed after a new network has been established.

1.6. Objective of this Paper

In general, learning the unfamiliar and conceptually understanding the subject-matter provides a large challenge – students have to learn how to make meaningful associations and construct further knowledge onto what they already know. However, the biggest of all challenges seems to be to change a student's already formed prior belief systems. This paper therefore deals on the ultimate challenge, of teaching to combat misconceptions.

In summary, this paper focuses on (1) how to promote deep understanding by instigating the students to question their inherent conceptual knowledge of how the world works, and (2) on how to correct these views should they be different form the scientifically proven views. This paper also reviews a few alternate methods of teaching that promote real learning, deep understanding and conceptual change.

2. Misconceptions and Conceptual Change

2.1. Defining Misconceptions

In its simplest form, a misconception is a concept that is not in agreement with our current understanding of natural science. Often these can be private versions of student's understanding of particular concepts that have not been tested extensively via scientific methodology. In the science education literature there is a dilemma about the word "misconception". It implies that there is something seriously wrong with an idea. Although, a misconception may not be in agreement with our understanding of science, they might nevertheless have varying degrees of logic and truth. Therefore many science education researchers resort to the term "alternate concept" (e.g., Wandersee, Mintzes, and Novak 1994). An alternate concept, then, is part of the student's private knowledge that is strictly speaking not completely consensual by scientific standards, though it may make sense to the student himself.

2.2. Common Student Misconceptions about the Process of Learning

Students entering our classes have a preconceived idea of what a lecture should be like. Like most lecturers, they think that a good lecture consists of clearly, logically and concisely formulated explanations of how the world around us works. Most students will think that in a good lecture all arguments will appear clear and logical. Indeed, we do want our students to follows our arguments, but ideally we want the students to do much more than that – we want them to critically think about what we are saying. Now, in contrast to passively listening, thinking is hard work, and unfortunately many students are reluctant to deeply think through a problem. Although deeply thinking through problems is in the end more rewarding, it initially might result in confusion, which is a state that not many students like. Thus, trying to follow clearly phrased arguments might not only be so much easier and less work, it superficially might even appear to be clearer and more logical. Students do not like being confused. The problem is that when going through the process of conceptual change an initial state of confusion is unavoidable. Thus one misconception that students have about of the process of learning is that a good lecture is always clear. The problem is that being "spoon feed" might cure the hunger, but it does not teach how to eat (or think) by yourself.

Another misconception students often have, deals with the nature of science. In contrast to what we, as teachers and researchers, know, they believe that science has all the answers and that these answers are always correct. It appears that for some reason those students have never learned that there might sometimes be ambiguities. Thus another misconception they have to combat is "that science is absolute".

Students often describe a good teacher as someone who knows all the answers to everything. However, telling the students the answers to questions might not always be in the best interest for the students. As teachers we want our students to be able to figure out the answers on their own and reach their own conclusions (which hopefully correspond to the scientifically correct answers). The problem is that as soon as students get told the "correct" answer, they like to accept and adopt it – in other words, as soon as the answer is articulated, in most cases, the process of thinking through a problem is stopped. The problem is that superficially thinking through a problem, only partially understanding it, and then accepting the final answer is so much less of an effort.

One strategy of dealing with these misconceptions is to tell the students directly – (a) the confusion is the first step to understanding a problem, (b) that science is not absolute, and (c) that you, as the instructor, will not give away answers but will prompt the students to try to figure out the answers by themselves. But as it is with all misconceptions, merely telling the students is not enough – they need to be convinced of each of those points by being confronted with non-working alternatives. They need to "experience" for themselves that (a) an initial confusion can result in deeply understanding a particular concept, (b) there really are intrinsic uncertainties in science, and (c) figuring out a problem by on their own is more rewarding than being told the answer.

2.3. Common Teacher Misconceptions about the Process of Learning

Perhaps the most common misconception that teachers have is that students do not just take in new information. Students are not blank slates but have preconceived theories of how the world around them works. Some of those preconceived ideas may indeed be scientifically correct but they do not always need to be – oftentimes student's ideas are based on personal experience that is coupled with their own versions of private logic. Sometimes concepts, however bizarre and peculiar they might be, can be well thought through. Especially those concepts will be resistant to change. The students have to be walked though all the different steps of the conceptual change theory (see next section), and even then conceptual change is not guaranteed to be successful. In other words, it is as good as impossible "to fix" misconceptions by replacing them with another theory, regardless of how much more scientific it might apparently be.

Sometimes, when teaching Physics in the traditional fashion, students might "accept" the scientifically correct theory, only within a certain framework – and often will "memorize" that theory only to pass the tests. Mazur (2003) illustrates this with a beautiful example from his own experience.

> "For example, after a couple of months of physics instruction, all students will be able to recite Newton's third law – action is reaction – and most of them can apply this law in numerical

> problems. A little probing beneath the surface, however, quickly shows that many of these students lack fundamental understandings of that law. […] The first warning came when I gave the test[1] to my class and a student asked 'Professor Mazur, how should I answer these questions? According to what you taught us, or by the way I think about these things?'"

The bottom line is that traditional methods of teaching physics do not always work, especially when the laws seem counter-intuitive to the students. Almost all alternate teaching methods that involve the student to participate more actively have been shown by various science education researchers to be more effective than the teaching-by-telling method.

2.4. The Conceptual Change Theory

Students' conceptual ideas are based on personal experiences, and require real changes in thinking (and adjustments at the neural levels). Unfortunately often students are not open to new ideas. In that case a rather radical approach is needed to change pre-existing concepts. With this in mind Posner, Strike, Hewson, and Gertzog (1982) proposed the conceptual change theory which is a combination of two theories: one from the history and sociology of science (Kuhn, 1970) and one from developmental psychology (Piaget, 1977). The process of doing science that Kuhn typified as assimilation of scientific results within a paradigm is similar to the way that Piaget described how individuals acquire knowledge. Kuhn's paradigm shift caused by the scientific revolution can then be compared to the accommodation of new knowledge in an individual that leads to a change of that individual's conceptual framework. One of the common instructional strategies to foster conceptual change is to confront students with discrepant events that contradict their existing conceptions. This is intended to invoke a dis-equilibration (Piaget, 1975) or conceptual conflict that induces students to reflect on their conceptions as they try to resolve the conflict. Following that, the students have to undergo the process of accepting, using and integrating the new concepts into their lives and even applying them to new conditions. Posner et al. (1982) hypothesize that there are four essential conditions for conceptual change. The steps can be summarized as: (1) **Dissatisfaction** The learners must first realize that there are some inconsistencies and that their way of thinking does not solve the problem at hand. (2) **Intelligibility** The concept should not only make sense, but, the learners should also be able to regurgitate the argument and ideally be able to explain that concept to other classmates. (3) **Plausibility** The new concept must make "more" sense than the old concept. It must have the capacity to solve the problem better. The learners should be able to decide on their own how this new concept fits into their ways of thinking and recall situations where this concept could be applied. (4) **Fruitfulness** The new concept should do more than merely solve the problem at hand; it should also open up new areas of inquiry.

A decade later the theory was revised due to an overemphasis on the rational aspects of learning and affective and social issues for conceptual change were incorporated into the

[1] Mazur developed several tests that focus on the students' understanding of the concepts rather then on reciting memorized laws and theories and applying them to numerical problems. Typical test questions can be found on his web-site at http://galileo.harvard.edu/home.html.

initial theory. They (Strike & Posner 1992) expanded on their theory and incorporated a wider range of factors that are needed to induce conceptual change. Further alterations to the conceptual change model have been discussed widely (e.g., Fensham, Gunstone, & White; 1994, Linder, 1993; Maloney and Siegler, 1993; Mortimer, 1995; Dykstra, Boyle, & Monarch, 1992; Niedderer & Goldberg, 1994; Chinn & Brewer 1993, 1998; Tyson et al, 1997; Blank 2000) and have been reviewed by Zirbel (2004).

3. Facilitating the Process of Learning

3.1. Shifting the Focus

It is fair to say that most instructors who teach science have the wish to teach comprehensively, provide the students with a deeper understanding of the world around them, and encourage these students to apply the newly acquired knowledge to other phenomena. Sometimes we even succeed, we may have the feeling that we have been successful, the lecture was well organized, very comprehensive and the students listened attentively. But later, when grading the tests, it becomes clear that a fair fraction of the students somehow did not get the main points. Reflecting back on the lecture, it can then seem rather puzzling to the instructor. Let's consider the ideal case; let's say the student does follow our nicely presented arguments. Do we know what the student will do with those arguments? Accept them? Adopt them? Integrate them into their current knowledge database and apply them to new phenomena? The point is that we do not really know what happens in the student's mind – all we know is how we think – and how we think the student thinks.

In other words, rather than focusing on our explanations and criticizing our teaching, it might be more effective to focus on the student and on how the student is learning. Not only is this approach much less intimidating, ultimately, it is also better aligned with our goal. After all, we would like the student to learn, to obtain a deeper understanding of the world for themselves, and maybe even apply the newly learned concepts to other situations. Only the student will be able to do this for himself. But what we can do is convince the student that he should do the learning for himself and that it might be profitable. In other words, teaching, by itself, is not enough. What we need to do is to initiate the students to do real thinking and thus engage them in the process of learning. However this implies a very different way of teaching and a different way of thinking from our side. We need to shift the focus from "lecturer centered teaching" to "student centered learning". While this might sound straightforward, it brings additional challenges. As instructors we are no longer just responsible for delivering the material comprehensively, we are in addition responsible for initiating "the process of learning" in the student's mind. Although we cannot be hold responsible for what happens in the students' minds, we are nevertheless responsible for effectively facilitating the process of learning in the students' minds.

3.2. Non-Traditional Teaching Methods

There are many different philosophies about teaching and several strategies have been tested. Current buzz-words are inquiry-based or hands-on teaching. About a decade ago the main buzz-word was constructivist teaching. Much of how to teach sciences in the classroom has been reviewed by Driver (1995).

Inquiry is used to describe a process of doing science. Inquiry is defined as a seeking of truth, information, or knowledge by questioning. It is a dynamic approach to learning that involves exploring the world, asking questions, making discoveries, and rigorously testing those discoveries in search of new understanding. In addition, it is central to scientific learning, itself. When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations. In this way, students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills.

Constructivism, a theory about knowledge and learning, attempts to describe how one "comes to know". This theory is based on the work of educational philosopher John Dewey (1938), and educational psychologists Lev Vygotsky (1978), Jean Piaget (1950, 1951 and 1971), Jerome Bruner (1966, 1990) among others. It refers to the notion that knowledge results from mental processes when individual "schema" interact with the "environment". Cognitive structure thus organizes experiences by allowing the individual to "go beyond the information given" by connecting those experiences to "prior knowledge". Real learning occurs when the learner actively engages in his or her own knowledge construction, integrates the new information into already present schema, and associates and interprets this information in a meaningful way. Our objective when teaching would then be to assure that the most fundamental concepts are well represented and connected in the students' minds, and that the learners are provided with the necessary tools for constructing further knowledge upon those core concepts.

An extension of Inquiry Learning and Constructivism is Critical Exploration. This term has been introduced by Inhelder, Sinclair and Bovet in 1974 and has been tested extensively by Duckworth (1997). This approach requires that the teacher engages learners in the subject matter and then, rather than telling, takes a stance in following the development of learners' thoughts. He or she then takes on the role of a facilitator and encourages students to make sense of their own thoughts.

What all of the non-traditional teaching methods have in common is that they involve the student to participate actively in the classroom. Various methods of teaching the sciences have been proposed in the science education literature. These include "Peer Instruction" (Mazur 1997), "Cooperative Groups" (Heller et al. 1992, Heller & Hollabaugh 1992), "Case Study Physics" (Van Heuvelen 1991a,b), "Think / Pair / Share" (Van Heuvelen & Maloney 1999), "Socratic Dialog Inducing Labs" (Hake 1987, 1992), "Ranking Tasks" (O'Kuma, Moloney, & Hieggelke, 2000), "Workshop Physics" (Laws 1991, 1997), "Studio Physics" (Wilson 1994), "Workshop Tutorials" (Wilson et al. 2002), "Micro-

Computer Based Labs" (Thornton & Sokoloff 1990, 1998, Sokoloff et al. 1999), and "Physics-by-Inquiry Tutorials" (McDermott et al. 1994, Shaffer & McDermott 1992, McDermott and Shaffer 1998).

3.3. Additional Suggestions that Provoke Conceptual Change

Zirbel (2005) suggests that to form new concepts or change old inadequate ones, the student has to be led through several processes. First, s/he has to consciously notice and understand what the problem is; second, s/he has to assimilate more information and try to fit it into already existing neural networks; third, s/he has to critically think through all the argumentation in his/her own words and reorganize this thoughts – s/he has to accommodate the knowledge and evaluate against his or her prior beliefs; and finally, s/he has to work towards obtaining fluency in the newly acquired and understood concept so that this concept itself has then becomes a mere building block for future, more advanced concepts. The claim here is that during the process of conceptual change what happens in the student's mind is a reorganization of his or her thoughts, the creation of new neural networks, and the rewiring of old ones. This process is difficult to provoke and requires the student to work hard. A good instructor can help with the process of conceptual change but cannot do it for the student. This section explains how an instructor may help facilitate this process.

Step 1: Hooking the student (Acknowledging Information)

The educator has to assure that the particular idea does get noticed efficiently. In other words, the new idea has to be dressed up enough so that it gets noticed and preferably also so that the student is initially intrigued by it enough to want to know more.

Step 2: Suggesting Bridges (Assimilating Information)

The material needs to be presented in such a simplified fashion that the student can follow every part of the arguments clearly. The student should at least have the feeling that something makes sense. Meaningful associations are particularly useful, because they might help the student make meaningful connections. Suggesting to the student how to chunk the information might be another way a good instructor might be able to help.

Step 3: Querying and Confronting the Student (Accommodating Information)

A good instructor will confront the student with why his or her prior beliefs no longer work. What is important here is that the student thinks aloud and articulates the problem in his or her own words. The instructor can guide the student by challenging the student with the right questions.

Step 4: Practicing and Constructing (Familiarizing Information)

A good instructor can now provide meaningful examples that go beyond regurgitating the problem, examples that involve applying the new knowledge and testing it. Also suggesting how to transfer the newly acquired concepts to other areas might also help. Clearly, the very last step, of making original discoveries is in the hands of the student himself. All a good instructor can do is to challenge the student to go beyond his or her limits.

3.3.1. Methods to Hook the Student

Most lecturers have their own personal way of "hooking" the students. Some lecturers are performers and will try to make the lecture more interesting by telling a story, others might resort to the telling of jokes. Others might perform an entertaining in-class demo. Yet others might use science fiction to make the material more interesting. All those methods can work (if done well) to capture the student's attention. Whether these methods actually affect the student's learning process is another matter. Science education research has actually shown that in class demos do not increase the total amount of learning going on in class (e.g., McDermott 2004, Crouch et al. 2004), if, and only if the students observe without thinking. Humor, if not used incorrectly, can distract from the problem to be analyzed and can, in the worst case scenario, even decrease the amount of learning going on in class. Nevertheless, all the instructor is trying to do at this stage is to make the student "notice" what the problem is and "pay attention" to the problem, i.e., engage the student enough in the problem so that he will continue to think through the problem. Clearly stating the problem and explaining why it is important is relevant here. Making the problem somewhat interesting may help. Here it is appropriate for the teacher to show personal enthusiasm in the particular topic. Anything to motivate the student will help. The student needs to clearly understand what the problem is and also show at least some willingness to want to resolve that particular problem.

3.3.2. Actively Assimilating Knowledge

The material needs to be presented in such a simple but straight forward fashion that the student can follow every part of the arguments clearly. In-class demons might help to "illustrate" the problem even more clearly. Cartoon drawings of the concepts might also be very helpful. Initially this approach is consistent with the classical approach of teaching, but in the end, it goes well beyond that. Initially the student should at least have the feeling that something makes sense. He needs to be able to put together different parts of information and combine that information with what he already knows. Thus making meaningful associations may be particularly useful. This may help the student to order the new information and integrate it correctly into his or her already present knowledge database. Analogies can also be rather helpful.

Initially the student does not have the necessary overview over the new topic and might not know which facts are more relevant than others. Stressing or repeating the relatively more important facts might be useful. Since deep learning consists of making connections between facts, particular attention should be paid to looking at the relationships between various facts and arguments. Causal thinking is called for at this stage. All arguments should follow logically and build up a coherent picture or story.

The idea is to provide the student with mechanisms of how to order the information and recall it in the largest possible chucks (i.e., interconnected concepts) of information. Suggesting to the student "how" to chunk the information might be another way a good instructor might be able to help. Again, examples or associations might be helpful. Suggesting how the problem could be personally relevant to the student is usually very useful. In fact, anything that makes a problem a personal experience for the student might be appropriate here. It can make any abstract physical concept a little more relevant. This will also help the student in paying undivided attention to what the teacher is saying. Any pedagogical and/or personal methods to motivate and engage the student in the subject matter are appropriate at this stage.

Usually this is where most teachers stop – the arguments, so far, have been stated clearly, meaningful examples have been provided, and important connections between various facts have been illustrated. In other words, the student has now been "optimally spoon-fed", but until now, he has not been doing any thinking of his or her own. Clearly, the student now needs to be guided to think through the problem on his or her own – and this will pose another challenge, as the student is now required to do the work. First, the student "himself or herself" will have to articulate the problem, explain why the problem is relevant, and what it is trying to resolve. Second, the student will need to be able to provide an outline of how to go about resolving the problem. Finally, he or she will have to really work though every single step on his or her own. In other words, he or she will have to "construct" his/her own arguments. This goes well beyond regurgitating the problem – it basically involves being able to explain the problem to fellow students in such a way that it makes sense to them. Some lecturers refer to this technique as "active learning".

Science education research has repeatedly shown that learning by listening and by even "seeing" (i.e., watching experiments) is not enough – the student will have to think through the problem on his or her OWN. Making the class brake out into small groups and initiating discussions in those groups is a technique that has been shown to be successful in some cases. It can be the next best alternative in large classes if the instructor cannot listen to all the students all at once.

Sometimes the students may go off on a tangent when articulating their ideas, or they may suggest a model that in not quite appropriate. Pedagogically the best procedure would be to let the students explore this tangent and make sense of it themselves. However often we are faced with time limitations in which case it might be appropriate to divert the discussion back to the original problem. How to confront the student with misconceptions, i.e., alternate conceptions, and/or with wrong models will be discussed in the next section.

3.3.3. Confronting the Student

Students entering classrooms are neither "blank slates" nor "empty vessels" that can be filled with information. Plenty of educational research has shown that students actively think about their surroundings and try to make sense of them to some degree. Even the youngest children will try to makes sense of their environment, observe it, and integrate the observations into their knowledge data base. A certain amount of curiosity is innate in the sense that we are born with it (Zirbel 2005). The implication of this is that students will often have prior opinions with how the world around them works. So then, since students do have opinions, why not ask them about their opinions and let them make predictions about certain experiments. This has two advantages (1) the teacher will get an idea about students' prior conceptual understanding of the situations and be alerted of possible misconception, and (2) the students can then, in the case of a misconception, be confronted with their own misconception.

The power of making predictions prior to demonstrations should never be underestimated, especially when dealing with somewhat counterintuitive concepts. Conceptual change is very difficult to provoke and it almost always involves a step where students need to be confronted with their misunderstandings or with some type of inconsistency. If the prediction is wrong it serves two purposes (1) the students will have to realize that something is wrong in their line or reasoning, and (2) conceptual change will be relatively more easily forced onto the students.

Again, like explained in the previous section, a very good method of how to deal with the construction of a more complex concept is to have the student articulate all the arguments by himself. In other words, the student has to do the explaining and the thinking (NOT the lecturer). The instructor has two job functions (1) ask the right guiding questions that will lead the student further in his or her arguments and (2) watch out that the student does not get sidetracked into a pitfall.

The teacher plays a very critical role here – he does not lecture, he merely "facilitates" the process of learning. Instead of volunteering suggestions, he should ask questions that will make the student reflect more deeply. Carefully phrased "guided inquiry" will have the strongest impact here. Since the student is going through a difficult process, including some unavoidable confusion, words or encouragement are always appropriate when the student tries to articulate his or her ideas.

There is one major dilemma with this approach – every student needs individualized attention and this method will not work well in a large classroom. A method that seems to work reasonably in large classrooms is the following: (1) Writing the question on the blackboard, splitting the class up into small groups, and initiating a five minute group discussion; (2) Writing every group's predictions onto the blackboard regardless of whether the answer is right or wrong (make sure these are the "group's" predictions – nobody likes to volunteer an answer that could be wrong); (3) Openly discussing the predictions – sometimes the students will already be able to rule out some of the options. This is a powerful technique of jointly and thinking through all the options (furthermore this approach will show respect to the students, including to those who volunteered somewhat dubious suggestions); (4) Then, doing the experiment (by now the students are generally pretty engaged in the experiment and will really pay attention); and finally (5) Jointly building a model for the case of the correct prediction.

3.3.4. Model Building

Model-building can be a very powerful way of learning to make sense of the problem. For example, when talking about electricity and circuits it can help the students to think in terms of water moving in pipes, or in terms of cars moving through the traffic, or even in terms of little green men jumping up and down in the conducting wire. The point is that it does not really matter what type of model the student is building as long as it is consistent with the concept to be understood and does ago good job representing it. But not all models will work – in the case of electricity the diffusion model will clearly be inappropriate.

It might be an educational experience to introduce the concept of model building as an option of how to do science. It is a worthwhile exercise to do in several small group settings, and it can work even in large classrooms. The role of models in science will need to be explained and students should then be encouraged to come up with possible models for a given situation. In small groups, students will then have to articulate their models and explain them to their peers. What is a very powerful experience for the student is representing the concept in his or her own words and constructing his or her own model. This is very different from suggesting a particular model to the student and explaining that in detail. This approach requires the student to be the "active" participant.

Again, as suggested in the previous session, various model suggestions can be written onto the blackboard and then openly be discussed in class. At this stage the instructor will play a critical role. When students make some suggestions he will have to ask guiding questions that dig deeper into the concepts to be discussed. Advantages, disadvantages, and possible limitations of the models also need to be discussed openly. Model building can be a very powerful – and personal – experience for the student and the student will have the feeling of "owning" the concept.

3.3.5. Trying Multiple Representations

No two students think alike. This is in part due to our individualistic character and differences in genetics and upbringing (e.g. Pinker 1997, 2002) and is also supported by the Multiple Intelligences Theory developed by Gardner (1993, 1999). The implication for teaching therefore is that not all students will think in the same manner and comprehend the material in the same fashion. Thus various approaches to teaching me need to be tried out. What might work for the auditory-semantic learner might not work for the visual-spatial learner, and vice versa. Furthermore, roughly 5 to 20% of all students suffer from learning difficulties that might interfere with their learning (e.g. Shaywitz 2004). These students, though deficient in some areas, might excel in others (e.g. Davis 1994, & West 1997). The trick, then, according to Gardner's Multiple Intelligence Theory, is to use a variety of different representations of the same concept. For example, we can use simple words to articulate a concept, or equations to describe the same phenomenon. Alternatively, we can use tables, graphs and diagrams to express the same concept. Sometimes a visual illustration or an in class demo can replace a thousand words. Students will make connections between the various modes of learning and representing the material, and this, in turn will provide them with a deeper learning experience.

3.3.6. Initiating Metacognitive Learning

A substantial amount of research (Baird, Fensham, Gunstone, & White, 1991; Blank 2000; Beeth, 1998; Gauld, 1986; Hennessey, 1991, 1993; Hewson & Thorley, 1989; White & Gunstone, 1989) indicates that conceptual understanding requires a metacognitive experience, where students discuss "how they know what" and "why they know what." Metacognitive learning is similar to the previous approach, where students make predictions before exploring and generate hypotheses. But in addition, students re-erect their old ideas and figure out themselves why these are wrong. Then they also suggest an explanation (they produce a second hypothesis) for the new (contradicting) results. Since this approach to learning loops back and provokes the student to reflect at each of the phases of the conceptual change model, it is referred to as "metagognitive learning".

It can be rather frustrating for the instructor to see how vehemently students may sometimes defend their own alternate views, even if the scientifically more correct theory "also" makes sense to them. Rather than trying to accommodate the new theory, they will instead look for arguments to re-accommodate their old theory, despite the fact that it does not fully solve the problem at hand. The metagognitive approach of looping back to analyzing students prior believes is particularly helpful in helping the student let go of his or her prior belief. On the other hand, this approach can also make the student a too critical and try to defend their own prior views even more strongly.

The dilemma with metacognitve leaning is that it involves a thorough discussion of how the student arrived at *both* the right and the wrong answers. This does not only take a lot of time, but is rather difficult to do in large classroom settings. Nevertheless, walking the student though individualized examples of how to reflect on one's own thinking can be a very meaningful experience for the students and can make the students understand that particular concept much more thoroughly. Furthermore it can provide a good opportunity to discuss the transfer of knowledge.

3.3.7. Inducing the Transfer of Knowledge

Ultimately what we would like our student to be able to do is to take the learned material and apply it to novel situations and have them make original discoveries of their own. Clearly this requires a very deep understanding of the material and goes beyond the walls of compartmentalized thinking (this means that the knowledge seems to be bound to situations in which it was first acquired). The transfer of knowledge is a very difficult process and is most certainly not automatic. Even if the student has understood the material in all its complexity, knows how to think scientifically, and is aware of metacognitive learning, the process of transfer will still remain a major challenge. Nevertheless, a good instructor can help here by encouraging the student to think outside the box, and perhaps quiz him for other situations where he could possibly apply the newly learning concept. Good everyday examples are almost always very valuable.

4. Pros and Cons

Most educators will want the student to be come experts in a wide range of fields. Clearly this goal is unreasonable since deep thinking requires a lot of time. There is only so much that can be learned in a given time. Furthermore, our brain capacity is limited and being normal human beings, we can only store and recall so much from memory. Thus tradeoffs have to be made between what is being taught and how that material is being taught. This section discusses challenges involved with facilitating the learning process of the students as opposed to giving traditional classes.

4.1. Quality versus Quantity

This is a much debated topic among many scientists and educators alike. There are generally trade offs between the two. Science education research suggests that going for a deeper understanding is still favorable, however there are definite disadvantages. For example, by going the route for deeper understanding, we might foster a population with many experts in narrow fields and with large voids in other fields. Clearly this is not the image of a well balanced person either. On the other hand, we have also seen that people with much superficial knowledge can only remember that knowledge for a short time and will not able to apply it to other related situations. Too much superficial knowledge is thus inert and unusable.

Another point to be made in favor of quantity, as opposed to quality, is that an in depth knowledge is not always necessary for us to function in today's society. For example, to be able to drive a car we do not necessarily need to know all the details of what happens inside the engine. All we require is a working knowledge and a training of how to drive the car. In other words, although depth might be interesting, it is not always crucial to how to survive in this current society. The point is that in some cases a deep knowledge is not always necessary. However, if we are trying to foster scientific understanding and critical thinking it clearly is a necessary ingredient. Thus we seem to need an in-depth knowledge in some areas while it might be considered to be optional in other areas. The trick, then, is to decide upon those areas where an in-depth knowledge is advantageous. And this is where a carefully designed syllabus becomes important.

A good instructor basically needs to prioritize the material and decide upon which topics need to be covered in depth and which ones can be covered more superficially. Those topics that are being covered in depth need to be chosen carefully and the basic core concepts need to be identified. These core concepts should then be taught so that students obtain a deep enough understanding to be able to construct further arguments from those concepts. All the knowledge that the students learn should be well connected and should make sense to the degree that transfer ought to be possible.

4.2. Disempowerment of Instructor

In the learner centered classroom, the role of the teacher is different than in the traditional classroom. The teacher no longer is giving standard lectures that have been well prepared and thought through a priori. Instead he resorts to guided inquiry questions that make the student do the thinking. Depending on the students and on how and what they respond, the lecture may go off on a slight tangent until all the points relevant to the argument are clarified and explained in depth. Incorporating the student responses into the flow of the lecture is something that cannot be prepared so well a priori. It requires that the teacher is able to think on his or her feet right there and then and will have some intuitive ways of responding to the students. Experience with this method of teaching is definitely very helpful. Furthermore, the teacher will need to feel comfortable with this method of conducting lectures as students are often very good in picking up on teacher insecurities and act out on that.

Perhaps one of the biggest differences to the traditional lecture is that the teacher no longer has complete control over how the lecture is going – after all, it in now the student whose answers determine the direction and the overall speed of the lecture. This might give the teacher the feeling of temporal disempowerment and make him feel more vulnerable. The only method of retaining control over the classroom is through the way he poses the guided inquiry questions and is leading the discussion. This process might feel uncomfortable particularly to anybody who has not tried out this approach of teaching before and who in not so familiar with standard student responses. Furthermore the students themselves might not feel too comfortable with this way of teaching – after all it is a rather personal experience to share one's way of thinking with the instructor, the discussion group, or even with the entire class. Thus the students, as well as the lecturer, might feel more vulnerable. A different type of dynamic will therefore have to be established in the classroom – a dynamic where the students respect each other, listen to each other, and share each other's ideas more openly. The teacher now has a different role in the classroom and this role requires a different set of skills. It requires the instructor to have extensive social skills – something which might be a real challenge to the shy scientist type personalities. The good news is that this method of conducting a lecture CAN be learned, but it might require a fair amount of experimentation before the teacher truly will feel comfortable with this student centered approach of teaching.

4.3. Dealing with Student Confusion

But it is not only the instructor who needs to do some major readjusting. The students themselves will also have to get used to this new approach to teaching and need to be willing to share some of their rather personal views. They will be challenged to think through all their arguments. This will be a particular challenge when dealing with somewhat counterintuitive situations or situations where the students have some prior beliefs. Letting go of deeply engrained beliefs is a major challenge, and the students will have to be walked through all the steps of the conceptual change model. They will have to realize that there is another theory that does an even better job at explaining the problem at hand. And they will not only have to accept the new theory, but also follow it, and understand it deeply. Often the students will then try to re-accommodate their prior belief and this process will continue until they are confronted with the fact that there are major problems with their prior belief systems. In other words, their prior belief will be challenged and this will inevitably lead to some moments of confusion.

Students do not like to be confused. In fact, being confused is an uncomfortable feeling for all of us and it is something we all like to avoid whenever possible. The only problem is that those moments of confusion in the lectures are unavoidable. They are part of a natural process that happens when changing minds. Thinking takes a major effort and thinking in a new fashion is especially challenging. This is something that does not come naturally or automatically. The student will have to struggle in order to accommodate the new theories into his or her prior belief systems. He will have to re-evaluate the situation and test his or her own ideas. This is a process that does not only take time, but also one that feels rather uncomfortable and sometimes even disturbing. But the point is that these moments of confusion are unavoidable when being confronted with any new theory, let alone with conceptual change. At those moments the students will need some type of "hand-holding" since these are truly challenging moments. Furthermore, they need to be told explicitly that confusion is unavoidable AND that it is a process that happens to everybody as they learn new material. They need to be told that confusion is the first step to understanding a new concept. However that is not all – students need to be "led through" some examples – they need to feel and experience such a confusion AND be led through it. In other words they need to experience that an initial confusion can lead to a clearer or more logical understanding of the material. Furthermore, they need to experience that resolving the confusion and deeply understanding the problem at hand is truly rewarding. They have to learn that an initial confusion is an integral part of learning.

Again, the students need to be told explicitly that confusion is unavoidable and that this is part of the process of leaning new material. If they are not told so they will feel frustrated, and blame the teacher for that feeling. Most students will tend to associate any feeling of confusion with the lecturer's inability to explain the material clearly. Students like to hear clear and logical explanations, and being challenged requires extra work. It is not uncommon for the teacher to get unflattering evaluations from the students. After all, anybody who challenges student's prior belief systems is going to be evaluated more critically (i.e., unfortunately more negatively) than anybody who lets the students retain their prior beliefs. The teacher needs to be aware of the fact that students truly struggle as they think through the arguments and try to accommodate the new material into their prior knowledge database. One method of making yourself popular again is by explicitly encouraging the student to go through the process of conceptual change and by making appropriate compliments after the students do understand that particular concept.

5. Discussion & Summary

So now, how does one teach best to provoke conceptual change? There are many different methods of teaching and every instructor will have his or her own style. Asking which teaching technique is best is analogous to asking which tool is best – a hammer, a screwdriver, a knife, or pliers. In teaching as in carpentry, the selection of tools depends on the task at hand and the materials one is working with. Books and lectures can be wonderfully efficient modes of transmitting new information for learning, exciting the imagination, and honing students' critical faculties, but one would choose other kinds of activities to elicit from students their preconceptions and level of understanding, or to help them see the power of using meta-cognitive strategies to monitor their learning. Hands-on experiments can be a powerful way to ground emergent knowledge, but they do not alone evoke the underlying conceptual understandings that aid generalization. There is no universal "one size fits all" teaching practice. Instead, depending on the goal and circumstances, it might be appropriate to combine various methods. For example, one might decide to embed cooperative group discussions into traditional lectures, or one could alternate between hands-on experiments and traditional lectures. The many possibilities then become a rich set of opportunities from which a teacher can construct an instructional program.

However there are a few guidelines. Setting a goal of what you want the students to accomplish and get out of this course is a good start. Also integrating effective assessment techniques into the lecture is another. It is important to continually ask the students what they think and help them construct the arguments in their own way (as opposed to telling them a nicely laid out logical explanation). In other words, how you, as the instructor think is almost irrelevant – the student will have to build up his or her own model that makes sense to him. The instructor thus has a rather different purpose in this type of classroom – instead of giving straight lectures (and these might be appropriate at times!), he stops and asks the students to do the thinking and watches out that the students do not just regurgitate the arguments but phrase them in their own words. The instructor thus "facilitates" the process of learning. In a large classroom setting the next best alternative to listening to individual students might be to initiate group discussions where the students are asked to explain the concepts to each other, or where the students are asked to use that particular concept to get a deeper understanding of the bigger picture. There are a few tricks of how to deal with those types of discussions – one would be to write all the answers by all groups on the blackboard (there is generally a limit to the possible answers) and then go through individual points jointly, evaluating each of the arguments. This way, some student misconceptions can surface – and the latter need to be discussed in quite some detail and it might need to be shown that those ways of thinking really do not solve the problem at hand. There is no shortcut of dealing with misconceptions – the students need to be walked through all the steps of the conceptual change theory.

This paper deals with how to teach in general to provoke a deep understanding of the subject matter. A deep understanding consists of logically and meaningfully interconnected concepts that form an even larger web of concepts. Deep thinking then involves being able to make further connections between the webs of concepts. Deep thinking involves the construction of new concepts and is almost always based on what the student already knows. Thus it is also very important to assure that the most basic concepts are profoundly understood and well connected. Constructing successive arguments on somewhat shaky knowledge, results in not-so-well connected further concepts. Thus, a thorough understanding of the most basic concepts is of utter importance.

This paper further argues that it is better to have a deep understanding in a few topics because it provides the solid foundation for building up further concepts upon them and because it can encourage the transfer of knowledge to new areas. In contrast, a broader understanding consists of superficial relationships between random facts and is relatively inert and unusable knowledge that most often will be forgotten relatively rapidly. The classic example is where students cramp lots of knowledge before a test to forget it soon afterwards. After all, what is the point of that type of learning?

The main drawback with guided inquiry and teaching for conceptual change is that it takes a lot of time. Since time is almost always limited in a lecture class, this poses a big question. Do we want to teach small amounts of knowledge in detail and cultivate a population of students with much knowledge in a few select areas – or – do we want to cultivate individuals who know a lot about a lot of things, but rather superficially. Ideally we want the individuals to be well rounded and still have some expert knowledge in some areas. So this means that traditional ways of lecturing, of conveying large amounts of knowledge in small chunks of times, cannot be ignored as a method to convey knowledge. However, and this is a main point of this paper, some areas need to be covered in substantial detail for several reasons. First, the students need to experience by themselves what it means to really understand a concept fully. Obtaining a deep understanding in one area is almost always a fulfilling and rewarding experience. Second, we all carry a whole set of misconceptions with us, and there is no easy and fast method of "fixing" those. Third, the students need to see how to thoroughly think through at least a few situations. They need to learn the process – the methodology – of thinking through a problem. And fourth, once they know "how to think" they might be able to transfer this technique to other situations.

So in summary, a healthy curriculum does cover some breadth, especially if we are dealing with a survey course, however some of the "basic" concepts need to be covered in substantial detail. The trick is to decide on which are the most basic concepts and to design a curriculum around that.

Facilitating the student's process of learning through guided inquiry does have other disadvantages too – in addition to the time issue. There is a shift of focus from lecturer centered lecturing to student centered learning, and thus there is a shift in power. It is an art to keep the classroom in control – which might be come an even larger challenge when trying to initiate additional group discussions. The role of the teacher is now rather different from the lecturer in traditional classrooms, and he needs to behave differently. Regaining control of a seemingly chaotic environment and still remaining the "facilitator" is an art. This is something that cannot be easily learned from text books, but takes years of experience, and almost more importantly, a solid and stable personality. It requires someone who is good in handling people and knowing what to respond when. Thus facilitating the process of learning might pose serious challenges for the inexperienced lecturer, but it certainly is something that can be learned.

Another disadvantage is that the process of building up concepts and constructing models requires deep thinking, which is something that takes a lot of effort. Therefore it is relatively common for the students to be initially relatively reluctant to this process. What students like, are logically and clearly spelled out arguments that – at least superficially – make sense when listening to them. Students generally like the idea of knowledge being "funneled" into their brains. The bad news, however, is that this approach is ineffective in making the students really think on their own feet, in other words, it does not work. Unfortunately students need to be told so repeatedly, because they will prefer to go the "superficially easier" way. It is not uncommon that students might frustrated with or even angry at the instructor. Thus, it is particularly important that the students really get walked in detail through some examples of how to build concepts – and personally experience that the end result is more rewarding than passively listening to the lecturer.

Dealing with misconceptions is also a delicate and sometimes rather painful experience. Letting go of prior, perhaps even deeply engrained personal views, is always a challenge. But what can cause real problems, is, that it can involve moments of confusion. Students do not like to be confused – and when they do get confused they often will blame the teacher for explaining the situation not quite well enough. Again, what an instructor should then do is to tell the students directly that confusion is a part of the process of thinking and that it is unavoidable. The best thing to do under those circumstances is to walk the students through those moments of confusion until to points really do make sense to the students. Personal words of encouragement might be appropriate here. This approach however, poses challenges to the large classroom setting. Perhaps the teacher could then focus on the majority of the students who understand that particular concept and then have them explain it to their peers. A final remark might be quite important here – any teacher who challenges his or her students will get challenged in return, and might therefore not get the most flattering end-of-the-semester evaluations.

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