

A HYPOTHESIS ON THE LEARNING PROCESS AS A BASIS FOR SCIENCE CURRICULUM DEVELOPMENT

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ABSTRACT

Misconceptions (also known as alternative conceptions) are a perennial problem in physics education. Research was focused worldwide on this, with limited successes achieved. The problem can be approached from different theoretical frameworks. This article identifies the following as historically predominant: the empirist-behaviorist, constructivist and student resource learning processes. These methods all lead to a dual epistemic, i.e. a physics vs. a pragmatic epistemic. A new hypothesis of the learning process in science is proposed, termed cognitive refinement. It identifies three levels of learning, viz. perceptual, conceptual and formal. Its implications for the science curriculum are discussed.

KEYWORDS

Conceptual change, learning theories, teaching strategies, curriculum

MOTIVATION AND PROBLEM STATEMENT

Students often perceive physics as a separate, isolated, academic world that differs from the real life they are living (Kruckenberg, 2006). In the science classroom, everyday concepts such as force and work have different meanings and obey other rules (laws and relationships) than outside it. For many students entering the science classroom, it may feel similar to entering a computer game or a Star Wars environment. As long as they apply the game's rules, they can succeed. When they leave the classroom (or switch off the computer), the "normal" concepts and rules are operative again. The irony is that science asserts that it describes the real world with concepts having their true meanings, and that scientific laws are the laws of nature.

The question arises whether the Newtonian mechanics that students learn at school and introductory university really describes the world experienced by the learners. Unfortunately the answer is no. For instance, nowhere on earth do we find a frictionless plane or anything that keeps on moving with constant velocity. One of the most prominent alternative conceptions of students relates to these two unnatural phenomena of a frictionless plane and constant velocity motion, namely the conception that any moving object needs a force in the direction of motion to keep it going (Vosniadou *et al.*, 2001). This alternative conception has been found amongst students from different cultures (Thijs & Van den Berg, 1995). It follows directly from learners' experiences since early childhood, e.g. that when a toy car or block is pushed, it soon stops and when they ride a tricycle or bicycle, they have to keep pedaling (apply a force) to keep it going.

Why do Newtonian mechanics start with the unnatural frictionless world and constant velocity motion? The answer lies in the nature of science and its development. Scientific knowledge is the result of a long history of public debate and critical exchange between highly specialized academic communities (Kruckenberg, 2006) that started about 300 years ago with Newton's Principia. In the positivist approach Physics developed into a formal, academic world that focuses on mathematical relations between quantities. To keep theory manageable, abstraction is used. In the scientific processes that

determine these mathematical relationships, some quantities are kept constant. Since the mathematics of an ideal situation is simpler (e.g. an ideal gas or a frictionless surface) it is used as a first approximation. When necessary, these ideal equations can be expanded to include additional factors such as friction or intermolecular forces. In physics we therefore use ideal situations in order to focus attention to specific relations and to simplify the mathematics. Consequently, Newtonian mechanics do not actually describe the real world in its complexity, but an ideal world of simple mathematical relations.

The introductory physics curriculum follows a positivist order. Standard textbooks invariably commence with a chapter on measurement and units. Then the physical quantities (or concepts) are introduced and defined operationally one after the other with increasing mathematical complexity. Recent introductory textbooks that incorporate physics education research strategies (e.g. Knight, 2004, Tougher, 2006, Hewitt, 2002) still adhere to this positivistic order of presentation. Attempts to change the order of presentation (e.g. Chabey & Sherwood, 2004) did not get much support.

During the past few decades, physics educators and researchers accepted the idea that students bring to the science classroom alternative or misconceptions that must be changed to the scientifically accepted concepts. The concept of force and Newton's laws are found to be particularly foreign to students (Vosniadou *et al.*, 2001). The force-motion alternative conception that a force always acts in the direction of motion, is particularly resistant to change. Conceptual change theories have become the dominant theory guiding physics education research and a variety of strategies have been devised to improve the learning of physics (Tyson *et al.*, 1997). A common notion of conceptual change strategies is that learners should become dissatisfied with their own conceptions which should be replaced with or transformed to the scientific ideas. An underlying perception is consequently that physics is the ultimate world of knowledge and all other ideas are alternatives or wrong.

Students are often blamed for focusing only on some specific features, e.g. the person that exerts the force (Kruckenberg, 2006). Objectively seen, when Newtonian mechanics is introduced, it also focuses only on some features. Unfortunately these features differ from what students experienced as important. In the case of the toy car, the student may focus on the stopping of the car, while the teacher attends to its motion. Introducing Newton's first law, the teacher may show the learners a toy car (or block) moving over a rough table or carpet and ask what would happen if this car moved over a slippery tiled floor, an icy surface or in outer space (in this order). The teacher thus relates to everyday experiences and guides the students towards Newton's first law. After Newton's first law is formulated and applied, his second law is introduced. In all the initial applications friction is neglected. The problem is that a frictionless world where most objects move at constant velocity is not part of the experience of students, which instead include friction and accelerated motion. When the teacher some weeks later adds that no work is done while holding your suitcase, the student whose arm gets tired from all the science books in the suitcase, feels really alienated.

The obvious question is how should this discrepancy between the learners' world and that of classical mechanics be resolved. Some propose that we accept that students will function in two separate worlds inside and outside the science classroom (Kruckenberg, 2006) as if living in two separate cultures, while others deem it important to integrate these worlds. Possible ways of integration are to implement conceptual change strategies, emphasize the nature of science or bring the curriculum closer to the needs and interests of the students. Although these strategies are reported to have some success, many learners still tend to operate in separate worlds.

Based on the cognitive model of information progression and developmental phases of learning we propose a strategy to incorporate physics into learners' experiential concepts. This strategy starts with the child's world of experiences (pragma cosmos) and develops it into a conceptual understanding of these and other learning experiences, finally formalizing it into the mathematical world of physics (cosmos theoria). The focus is on the *refinement* of learners' existing cognitive structures instead of conceptual *change*.

THEORETICAL FRAMEWORK

Cognitive model of learning

Over the past 50 years much has been learned from studies in cognitive science, neuroscience and education, about how the mind works and how learning takes place (Redish, 2003; Gagne, 1985). This knowledge influenced contemporary teaching and learning strategies. A cognitive model can be used to illustrate the working of the brain when learning takes place (Redish, 2003). Memory is a highly complex and structured phenomenon, but we'll only attend to some aspects of information-processing that is relevant for effective teaching.

According to the cognitive model three memory components are active when learning, namely a sensory register, short-term or working memory and a long-term memory (Weiten, 2007). The stimulation that a learner receives from the environment is transformed to neural information that enters the sensory register where it persists for a very brief interval. Only some features of the 'picture' recorded in the sensory memory (selective perception) enters the short-term or working memory. Selective perception depends upon the learners' ability to attend to certain features while ignoring others. Novice and experts in science may thus focus on different features of an event which they consider relevant (Gagne, 1985).

The working memory serves as temporary store for incoming information and appears to be the part of our memory that we use for processing information and problem solving (Redish, 2003). The working memory is limited and has a short lifetime of only a few seconds. Search processes may be initiated in the working memory to retrieve material stored in the long-term memory by previous learning. According to Gagne (1985) a learning occurrence takes place when the stimulus situation together with the content of memory affect the learner in such a way that his or her performance changes.

From the standpoint of learning, the most critical transformation of information occurs when it leaves the short-term memory and enters the long-term memory (Redish, 2003). The information available as certain perceptual features in short-term memory is now transformed (encoded) into a conceptual or meaningful mode. The information stored in the long-term memory is organized into knowledge structures. A knowledge structure is a pattern of association of knowledge elements. A pattern that tends to activate (made accessible to working memory) together with a high probability in a variety of contexts is often referred to as a schema. An example of a schema of motion is that objects tend to stop (Redish, 2003). Some of students' schemas formed before instruction may be more coherent than we as scientists tend to give credit for. Since new knowledge is built only by extending and modifying existing schemas, students' existing knowledge is the raw material we have to work with to guide their learning.

Developmental phases of learning

From the cognitive model of learning emanated ideas of developmental levels or phases in learning. Three examples are concept learning of Gagne (1985) and Ausubel (1968), language learning (e.g. Weiten, 2007) and the Van Hiele theory of development of geometric thinking (Van Hiele, 1986). Gagne (1985) proposed stages of learning a concept. It begins with the discrimination of features of the concept from that of other concepts, followed by generalization of the concept by multiple experiences and finally mastering the concept when the relevant qualities have been abstracted and can be applied to new examples. Brookes (quoted by Gagne, 1985) argued that a learner is likely to acquire the initial concept representation from a particular instance, which may be the first (and not necessarily the best) instance. Subsequent encounters with other instances can bring about changes that may alter the stored representation of the concept toward a general perception. However, such changes will continue to depend upon the particular instances and situations encountered by the learner.

From his studies of structure and insight in geometry learning, Van Hiele (1986) deduced a five-level hierarchy in the development of geometric thinking. The levels are: visualization, analyses, informal deduction, deduction and rigor. These levels are sequential, but not age-dependent in the sense of the

developmental stages of Piaget (Van de Walle, 2003). Geometric experience is considered as the greatest single factor influencing advancement through the levels. Instruction or language at a level higher than that of the student will result in a lack of communication which may cause rote learning. The Van Hiele theory became the most influential factor in American geometry learning (Van de Walle, 2003).

Weiten (2007) discussed milestones in language development. Features of human languages are that they are symbolic, generative and hierarchically structured. Apart from echoing sounds, three milestones in a child's language development are morphemes, phrases and sentences. The smallest units of meaning obtained are morphemes that include root words as well as meaning-carrying units as the past-tense suffix 'ed'. The meaning of a word is broadened and generalized by using it in different ways. In the next phase the child combines words into phrases, after which he forms sentences. Complex rules of syntax govern the construction of phrases and sentences. These complex rules are studied by language specialists and researchers. A child's language acquisition therefore develops from words that are given meaning by his/her experiences, to the building of relations between the words in phrases and then to form sentences that haven't been used before. Sentences reveal the competency to use words with their correct meaning in the correct relation to other words and according to the rules of the language. Before they have mastered these competencies, it would be of no use to teach children formal linguistics and distinguish between verbs, nouns, etc. Children must first synthesize the words into sentences, before they can analyse these sentences.

The following three aspects that emanate from the theoretical framework informed the hypothesis of the learning process proposed in this paper:

- a. Learning is a process of progressive construction of personal cognitive structures.
- b. All learning starts from experiences. Selective perception of attributes induces, strengthens or alters the formation of concepts. Formalization can only follow from a conceptual understanding.
- c. Learning is developmental. Learners should proceed through different phases in a definite order to master a concept. Previous phases are prerequisites for successful attainment of following phases.

GENESIS OF LEARNING THEORIES

To place the hypothesized learning process into perspective, three models of the learning of physics are discussed. These models are based on the empirist-behaviorist, conceptual change and student resource theories and are illustrated in Figures 1, 2 and 3.

The empirist-behaviorist theory was dominant in the first half of the twentieth century, before the development of the cognitive model from neuroscience. The so-called traditional curriculum over-emphasized experiences as the means of learning. In physics, carefully selected laboratory experiments were used to illustrate and confirm the formal theory of physics. This learning process is illustrated in Figure 1. Because learners' existing concepts formed from everyday experiences were not attended to, cognitive structures separate from learners' existing structures were formed in the physics classroom. Physics and reality seem to be parallel, but analogous universes.

Constructivism is one of the major theories that built on the cognitive processes of learning. Ausubel, a forerunner of the present constructivist teaching approach (Trumper, 2003), asserted that "The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly" (Ausubel, 1968). Psychological educationalists agree that all learning commence with experiences (e.g. Ausubel, 1968; Gagne, 1985 and Vygotsky, 1986). Experimentation provides learners with both hands-on and minds-on experiences and is therefore an ideal way to enhance constructivist learning. Due to the cognitive model of learning, the constructivist theory emphasizes conceptual learning to precede formalization of concepts. The inclusion of conceptual understanding as a phase in the learning process (Figure 2) is a major progression from the empirist-behaviorist process (Figure 1). Actual learning is perceived to take place in the learners' working memory during the construction of cognitive structures (Redish, 2003). Physics education researchers acknowledge the existence of

scientifically wrong structures formed by learners before (or even during) formal tuition and devise learning experiences for conceptual change of these so-called alternative conceptions. Conceptual change often involves discreditation of learners' existing cognitive structures by means of conflict situations (Scott *et al.*, 1992).

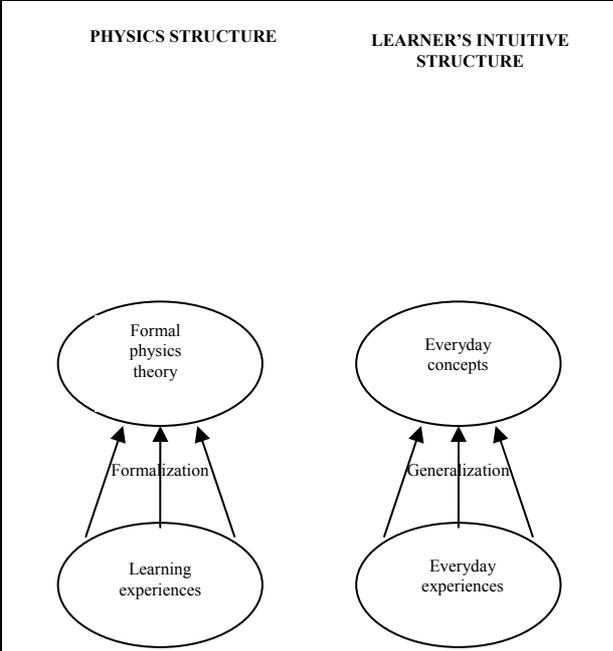


Figure 1: Empirist-behaviorist learning process

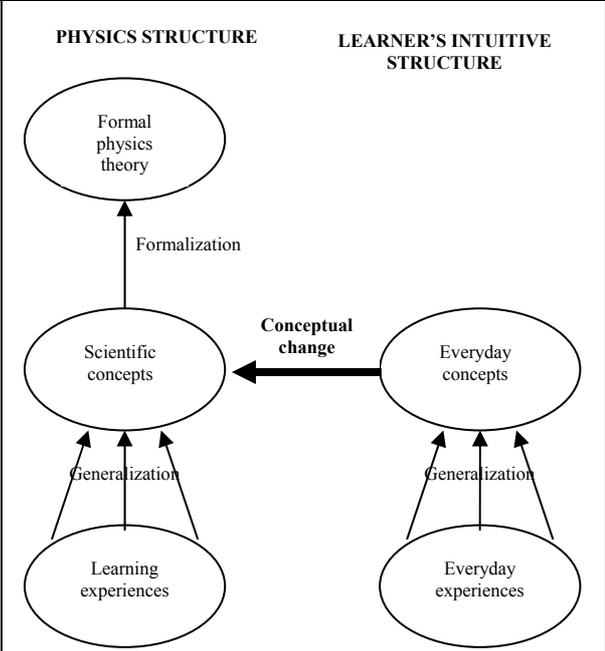


Figure 2: Conceptual change learning process

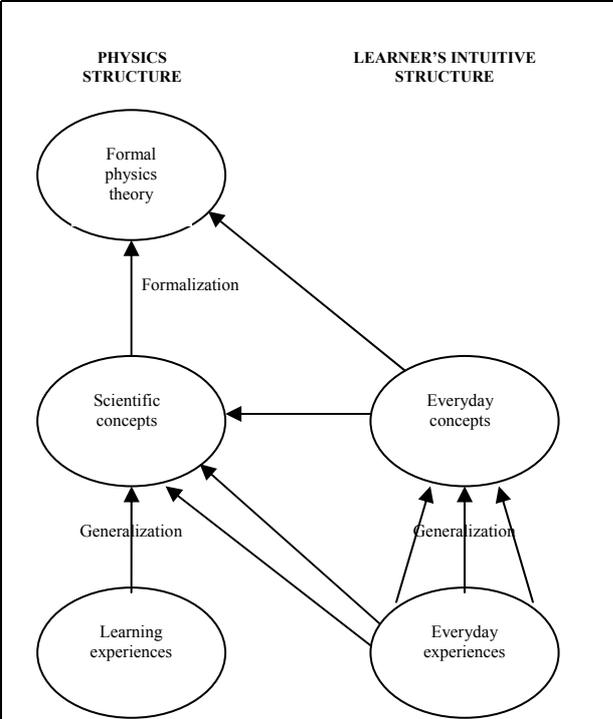


Figure 3: Student resource learning process

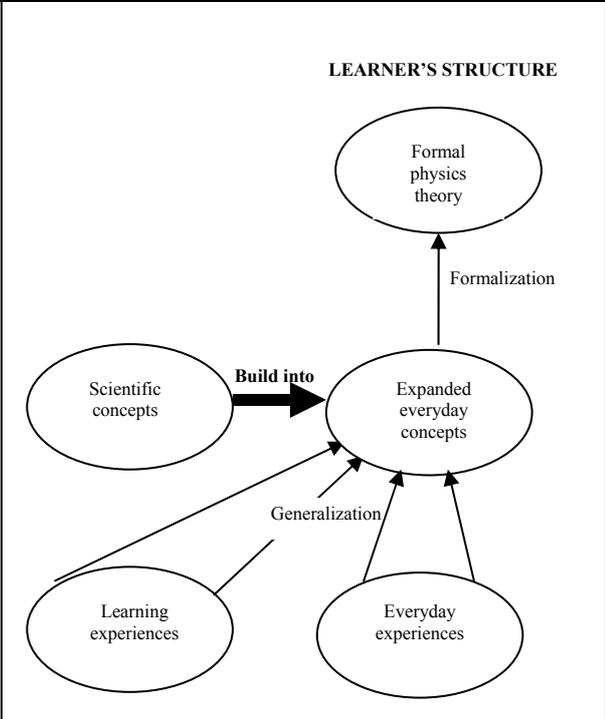


Figure 4: Cognitive refinement learning process

Within the framework of inquiry and constructivism a variety of strategies for physics learning are found (Redish, 2003), e.g. microcomputer-based learning (e.g. Sokolof & Thornton, 1997), inquiry-

based learning (e.g. McDermott, 1996, Abd-el-Khalick *et al.*, 2004); Socratic dialogue inducing laboratories (Hake, 1992), workshop physics (Laws, 1991), peer-learning (Fagen *et al.*, 2002), problem-solving (e.g. Leonard *et al.*, 1999; Taconis & Broekenkamp, 2001, Gaigher *et al.*, 2006) and authentic science (Charney *et al.*, 2007). Although successes have been reported by the implementation of various strategies, learners still seem to function in two separate worlds in and out of the physics classroom (Kruckenberg, 2006). Learners' alternative conceptions are found to be extremely resistant to change (Driver *et al.*, 1989) and the parallel-universe problem is not successfully resolved. Although learners' alternative conceptions are often brought to the open in the classroom, they are not effectively integrated with existing structures.

Instead of focusing on learners' misconceptions and difficulties, Hammer (2000) advocated the use of learners' existing cognitive structures as resources for further learning. His proposal relates to the idea of "anchoring conceptions" of Clement *et al.* (1989), Minstrell's (1982) "bridging analogies" and the "refinement of intuition" described by Elby (2000). These strategies use and modify learners' cognitive resources as raw material from which they may construct a physicist's understanding (Hammer, 2000). Features of student resource learning are illustrated in Figure 3. The epistemological-focussed curriculum of Elby (2000) was designed to integrate conceptual development with epistemological development. *Students were helped to understand that learning physical laws involves refining one's intuitive ideas in order to reconcile them with physics.* This idea is represented in Figure 3 by the arrow pointing from learners' concepts to the formal physics theory.

A study of the strategies depicted in Figures 1,2 and 3 shows that two aspects were not taken into account. The first aspect is the personal experiences of the learners that caused the formation of their intuitive concepts. Conceptual change strategies try to reconcile learners' concepts with that of physics by learning experiences in the laboratory or classroom, and even by reference to real-life situations. These learning experiences however, focus on discrediting learners' existing concepts and convincing them of the correct physics, instead of starting with the experiences behind the alternative conceptions. For example, consider again the force-motion alternative conception and the teacher's strategy given previously. The teacher focuses the learners' attention on the increasing distance of motion of the toy car in order to teach Newton's first law, and pays no attention to why it eventually stops or (if asked about it) casually asserts that it is "because of friction". According to the cognitive model, it is possible that the learner will not even extract his alternative conception from the long-term to the working memory, because no cues were used. Since the features that the teacher focuses on differ from those that caused the learners' alternative conceptions, a separate cognitive structure will be formed. However, this structure will possibly not make much sense to the learner or not be strong. Therefore it may be abandoned the next time that the learner sees an object stop, or gets tired when riding his bicycle. *It must be remembered that the cognitive structures that the child has formed by repeated personal experiences provides him with satisfying explanations of phenomena and are therefore given prominence above those learned in the classroom.*

From this example it follows that it is of utmost importance for effective learning of physics, to start with everyday situations experienced by the learners that gave rise to the formation of the alternative (or better: primary) conceptions. In the beginning of the teaching of force and motion, the relevant primary conceptions should be retrieved and the learners should be guided towards an understanding of the scientific explanation of their experiences that caused them, e.g. the experiences that all moving objects on earth eventually stop and that a force must be exerted in the direction of motion to keep the objects going. The force of friction should therefore be introduced very early in the study of forces as explanation for their experiences. Thereafter, their attention can be focused to the abstracted (idealized) motion of objects and they can be guided towards the understanding of Newton's laws. Throughout the learning, reference should be made to previous personal experiences, for example that a boy's toy car can move at constant velocity along the pavement if he pulls it with a force equal to that of friction, and a girl's doll pram can be pushed at constant velocity along the pavement. These examples explain why one has to exert a force to keep your bicycle going, etc. Learners who have pulled and pushed objects in the class and formed mental images of previous experiences (girl pushing her doll's pram, and a boy

riding his bicycle), and understand the scientific explanations of these experiences, should more readily expand their existing knowledge structures permanently to incorporate scientific knowledge. *The scientific concepts and learning experiences must be additional (not alternative) inputs to learning.* Physics concepts should consequently be cognitively internalized by the students. This strategy is illustrated in Figure 4.

Another aspect that should be taken into account is that novice learners perceive physics as an alternative universe (cosmos theoria) while their own experiential universe (cosmos pragma) is real. Learners' ideas cannot easily be transferred to the physics universe, as if by "religious" conversion. Physics should instead be built into their existing worlds. This is in accord with the cognitive model. In the learning process, the existing structures of the learners should be explicitly recalled into the working memory, and the new knowledge (physics) should be incorporated with them. This recall of existing structures can best be accomplished by the learning experiences that formed them in the first place. Focusing on the features that form learners' primary conceptions and giving scientific explanation for them, should be the first step in the learning process. We suggest the term *perceptive learning* for this, because perception is "the action by which the mind refers its sensations to external objects as cause" (Sykes, 1976). The next phase is the *conceptual level*, where learners' cognitive structures are refined by extension and guided to an understanding of physics concepts. At the *formal level* the conceptual structures are recalled and expanded to include formal physics, i.e. operational definitions and other mathematical relations as well as physical laws and models. Learning in the formal level should include the nature and processes of science, e.g. that complex real-life situations are simplified to determine the influence of different factors. In this phase, frequent reference should be made to the personal and laboratory experiences from which the second phase emanated. Otherwise physics will become just a manipulation of formulas and solving of formal problems that has nothing to do with everyday-life.

CURRICULAR IMPLICATIONS

The learning process illustrated in Figure 4 necessitates the re-thinking of the presentation of concepts such as force, as well as the order of presentation of the physics curriculum as a whole. Regarding the force concept, a conceptual understanding of the forces experienced in motion, including friction, should precede the formulation of Newton's laws. It is also necessary that the entire physics syllabus is revised. Lemmer & Lemmer (2007) proposed on philosophical and didactical reasons that classical mechanics should commence with a study of the concept of energy, instead of force. A discussion of these examples of the order of presentation of force and Newton's laws, as well as classical mechanics, follows.

The learning process of cognitive refinement can be applied to all fields of physics learning (e.g. mechanics, electricity) especially at school and introductory physics, where primary conceptions have to be refined to incorporate basic physics concepts and scientific explanations of phenomena. In electricity, for example, most learners think that the battery delivers electric current that is consumed by the bulb in the simple electric circuit. The perceived consumption of electric current is often counteracted in the science classroom by letting the learners measure the current in different places in the circuit. A conceptual conflict situation occurs when the measured current remains constant. The learners may remember this, but it does not make sense to them because it does not resolve their alternative conception. Their experience that the battery goes flat implies that something is consumed. Before learners can understand why the current remains constant in the series circuit (and form a proper cognitive structure), they must be given an explanation to their existing problem. This can be resolved by the scientific explanation that a battery becomes flat due to energy conversions in it, and that the bulb converts electrical energy into light and heat energy. With energy conversions identified as the "culprit" of the flat battery, they readily accept that the current can remain constant. A model (e.g. the "garden hose" model) to explain this, can aid in building the scientific perception of current.

The examples from mechanics and electricity strengthen the argument that the physics curriculum should commence with the concept of energy before force or electric current is introduced (Lemmer &

Lemmer, 2007). This makes sense pedagogically in terms of the cognitive model and developmental phase theory. Learners' intuitive ideas about energy do not differ as much from its scientific expression as in the case of force or electric current. Trumper (1990 & 1991) presented instructional strategies to guide learners' creation of new scientifically correct schema based on their own preconceptions about energy. Duit (1981) proposed the use of semantic anchors to improve their everyday understanding of energy conservation. The scientific concept of force is, however, abstract and differs so much from everyday meanings (primary concepts based on experience) that concept development from learners' intuitive ideas (perceptions) are difficult. Changing the order of the physics curriculum to commence with energy also makes sense in terms of learners' perception of energy as *causa motio* and as internal drive and maintainer of motion. This perception only needs to be reinforced and extended, not changed. Introducing energy as the *causa motio* can prevent the formation of the force-motion alternative conception. Learning can then commence with the understanding that work has to be done to change an object's energy ($W = \Delta E$). Then force can be introduced as the agent that does mechanical work. Force is then perceived as the *changer* of motion (causes acceleration). A conceptual instead of a positivist order of presentation of the physics curriculum should therefore start with energy, proceed with work and end with force and culminates into Newton's laws.

The most important aspect in the second phase of learning is generalization of the concept and the building of relations with other concepts in order to establish its scientific meaning. Since conceptual understanding precedes formalization, existential relations should be introduced before operational relations. For instance, the concept of work as the change in energy may form part of the second phase, while mechanical work as the vector product of force and displacement is formal and belongs to the third phase of learning.

It is important to note that learners can be on different levels for different concepts simultaneously. For instance, they could already have formalized the concept of energy before the concept of electric current is introduced on the perceptual level. One should realize that all new learning, even that of an esteemed physicist, is much easier if they can form a mental image of a new concept or idea. These mental images should relate to previous experiences, in or out of the laboratory. That is the benefit of examples and illustrations.

CONCLUSIONS

Although physics education researchers reported some successes in the implementation of a variety of constructivist teaching strategies, physics remains foreign to most learners, and learners often fall back to their existing alternative ideas. This implies that physics concepts have not been cognitively internalized and that learners live in "parallel universes" existing inside and outside of the classroom. The problem with current implementations of the cognitive model to physics learning, is that we as physicists look at the situation through our own schemas (a remark of Redish, 2003) instead of from the perspective of learning as the construction and reconstruction of personal schemas. Therefore we use formal experiences (e.g. in the laboratory) or formalize real-life experiences in order to form physics concepts instead of the everyday-life experiences (anchoring experiences) that caused learners' initial cognitive structures.

From the cognitive model of learning follow two important aspects, namely that all learning starts with experiences and that learners build their own personal cognitive structures. Both these deductions should be considered when teaching physics. Over-emphasis of the experience and neglect of the knowledge structures, leads to the empirist-behaviorist ideas. On the other hand, the constructivists' over-emphasis of the structure formation and neglect of personal experience leads to ineffective conceptual change theories. Everyday-experiences of learners, especially those that have been formed and strengthened repeatedly since early childhood, are resistant to change. The child cannot be transferred to the world of physics. The world of physics can only be built into (or grafted onto) his existing world. Consequently, his everyday experiences should form the starting point of learning if we want to transform them into scientifically correct structures. These conceptual structures can then be

refined towards formal physics that includes operational definitions, mathematical relations and problem solving.

Personal real-life experiences form the anchoring experience, not only for the novice, but also for the expert, and on all three levels of learning. A conceptual understanding of these and other experiences (in the classroom or laboratory) form the second level of learning where learners are guided to generalize their experiences, understand the scientific concepts and form conceptual relationships between concepts. Contemporary strategies such as inquiry laboratories, peer-learning, authentic problems-solving, etc. can be used effectively on this level.

To summarize: We contend that any learning strategy that results in a dual epistemic ("parallel universes" of reality and physics) is not effective. The current conceptual change theories are still based on this dual epistemic. The attempt to effect conceptual change is an attempt to transport learners cognitively from reality to theory, which is akin to a religious conversion. Instead of conceptual change, the teacher's task is to facilitate (guide) the grafting of scientific thinking onto the trunk of the pragmatic epistemic, thus refining the latter to formal scientific theory. This refinement can be a radical development, but should not lead to fundamentally different conceptions.

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