# LEARNING, LEARNING CYCLES, AND LEARNING ENVIRONMENTS

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**Abstract:** In recent years, research into (science) teaching has revealed shortcomings of standard approaches. Our students do not learn what we would like them to learn. If our goal is to let students participate in conceptual development, and if we want them to understand how science works and can be applied, new methods of learning are required. This paper investigates learning processes in physics and proposes to create an integrated learning environment in which students can learn physics by practicing it rather than listening to a teacher.

## 1 Introduction

For years now I have concentrated on the conceptual structure and development of physics in my teaching. It appeared that if students were to gain the necessary tools to apply physics in engineering they would have to understand the concepts underlying the models of physical processes. So I set out to make the inner structure of the theoretical body of physics as plain and clear as humanly possible. At the same time I collected a repertoire of mistakes made by students which I applied in my teaching. My students should have the benefit of knowing the pitfalls of learning a science such as physics. They should be forewarned and therefore prepared to do the right things at the right moment. Naturally, we applied the concepts and didactic information to many of the standard physics problems, giving my students ample opportunity to study and practice problem solving.

First, I realized that most of my students were immune to my teaching of concepts and to my warnings. They steadfastly kept applying what may be called intuitive or everyday concepts, or concepts they had been exposed to in previous schools. I remember one student saying impatiently to me ”Whatever…”—after I had admonished him for about the fifth time that energy is stored in a compressed spring and not momentum. Obviously all the teaching about the importance of conceptual understanding had not made a dent in his mind. I was equally struck by the body language of a student giving a wrong answer to my question of how to find the distance travelled by a body.[1] Her entire demeanor implied: “Now I told you, and that’s it…” I could see that she was completely satisfied by her rather typical—and typically wrong—answer. Not the slightest doubt as to the correctness of her response remained, despite all she had learned about motion at variable speeds. Indeed, when confronted by me to think again she changed her answer after much hesitation and then acknowledged that she had actually learned how to do it right.

As the years went on I began to notice a second type of shortcoming in the learning of my students. I had begun to develop an explicit modeling strategy for solving physics problems. I became convinced that my students needed clear and strong strategies for tackling problems. My colleagues and I had started to emphasize generalized dynamical processes in our teaching and we designed the necessary conceptual and practical tools to deal with the novel approach and applications.[2] We were convinced that we had found what mattered, and we built our didactic strategies around teaching our students the necessary skills to deal with the problems we wanted them to be able to solve.

Again I was struck by the refusal of my students to accept new strategies and procedures. To this day, despite concerted efforts at a practical implementation of the necessary learning processes, my students invariably resort to tried and trusted—but completely ineffective—methods learned in high school physics when they are asked to work on an exam. No matter how strongly I emphasized the importance of proper strategies, and how often I demonstrated them, my students seem immune to learning new tricks.

Clearly, this situation—which is by no means unknown in the physics teaching community—is disturbing. It finally set me on a path of exploring what may be the causes of what I have observed, and to find remedies for it. Actually, before I started thinking about the causes I began to design a kind of dual “learning cycle”—composed of modeling and experimental cycles—and to transfer my teaching to an integrated learning environment in a studio setting. The

1. A body moves at variable speed. How do you find the distance travelled? The student’s answer was simple and direct: “…speed times time.”

2. The physics course designed by Werner Maurer and myself may be called “physics of dynamical systems and processes.” It rests upon the structure of continuum physics and makes use of system dynamics modeling. See Fuchs (1987a,b, 1996, 1997a, 1997b, 1998), Maurer (1990), Borer et al. (2000).

learning cycle is supposed to organize one's action—the doing of physics—whereas the learning environment should house the learners and give them the means for their activities. Meanwhile, three authors, Georges Ecoffey of the UAS at Fribourg, Edy Schütz of the Berufsschule Uster, and I are working on a real and a virtual Integrated System-dynamics Learning Environment (ISLE).[3] In the real environment students can learn physics by engaging in the activities of experimenting and modeling. The virtual environment is planned to be a model of the real one implemented on a computer.

In my search for the causes of my students' actions and behaviors I have found that much has been learned about learning in recent decades that directly relates to the challenge I am facing every day. Philosophers, educators, psychologists, and scientists have contributed much to an understanding of the process of learning in general, and in the sciences in particular.[4] Many researchers and teachers believe now that learning is a constructive process, learning cycles and learning environments are ubiquitous in discussions of the improvement of science teaching, and inquiry based learning has become a household name in science teaching.[5]

A particular question—and a tentative answer—stand at the beginning of my investigation. Are the two types of difficulties demonstrated by my students—conceptual and procedural—independent or are they related? If they are, is one of them the cause of the other? I have slowly come to believe that the lack of procedural knowledge, actually, the lack of appropriate practical behavior, is more fundamental than the conceptual problems. More and more I feel that if my students are to better understand the concepts of physics they have to learn to change their behavior, i.e., their solution strategies and work habits. I hope that learning of concepts and content simply results from an adequate grappling with physics in settings which emphasize procedures, processes and projects over rote learning.

## 2 LEARNING FOR BEHAVIORAL CHANGE

Learning is a complex multifaceted phenomenon. I am only beginning to understand a few of its aspects. To make sense of it I have to limit myself to one or two features. Essentially, I will try to discuss learning processes that may lead to real change in a person—first behavioral, then conceptual. In Section 3 I will answer the question of how these processes can be designed and organized, and in Section 4 we look at how they can be implemented and what tools they require. In Section 5 we look at what physics education research has to offer.

3. Fuchs, Ecoffey, Schütz (2001).
4. Dewey (1910, 1946), Piaget (1954), Schank and Abelson (1977), diSessa (2000).
5. Lawson (1995), Linn and Hsi (2000), American Association for the Advancement of Science (1986-).

### *Students' Problem Solving Strategies*

Let me be specific and present the example of an exchange I had with a student recently. As mentioned before, I have been emphasizing solution strategies for problems that are more demanding than the simple ones that only require finding the right equation and plugging in some numbers. In essence, the solution procedures require explicit modeling which can be broken down into some fairly simple and clear steps.[6] Students get the opportunity to watch me use the modeling approach, and to try it out for themselves (and in groups) on problems during class time and at home. I have been warning my students that unless they use new strategies they will fail in their attempts to answer even modestly complex questions.

A student came to me after receiving a bad grade in an exam. In attempting to solve the problems he had mostly resorted to methods he knew from before studying college physics. After handing back the exam I had told the class—as I usually do—to try the exam again at home, if necessary with the help of the detailed solutions provided. This student came and said that he had studied my solutions carefully, then put them down and done the exam again. When he checked he noticed that he had made the same mistakes again, and used the same old strategies that did not lead to success. He wanted to know what was the matter.

Well, I wanted to know what was the matter too. Students rarely work on an exam again at home, and they hardly ever come to discuss it with me afterward. Usually I discuss some problems with the class a week or two later. So I was intrigued to get a chance to talk to a student and possibly find out what he was thinking and doing. To make a long story short, he told me that he resorts to old habits because in the past they proved to be successful. Why was he doing this? Why could he not follow my advice and use new procedures he had seen and practiced? Wouldn't his experience in class and the threat of bad grades provide enough incentive for behavioral change?

I will attempt to give a possible answer to these questions. First we look at a learning problem in a very young child which to me exhibits striking similarity with what I saw this student struggling with. Then brain functions will be discussed which help explain how learning occurs in the young child. Finally I want to describe what this all may mean for my students learning physics.

### *Laurent Piaget's Quest for the Right Side Up*

Jean Piaget subjected his baby son Laurent to an interesting experiment.[7] Here I will use the

6. See Hestenes (1987, 1992), Halloun and Hestenes (1987), for a traditional modeling approach. If suitably generalized, the well known procedure from mechanics—creating a free body diagram, writing down the law of balance of momentum, and formulating constitutive laws—applies to all fields of the physics of dynamical processes; Fuchs (1997a,b; 2002).

description of the story provided by Anton Lawson.[8] Baby Laurent had learned to hold his milk bottle and to lift the nipple to his mouth and suck. Then, one day, his father began to present the wrong end of the bottle to his son:

> *…Laurent is subjected to a series of tests, either before the meal or at any other time, to see if he can turn the bottle over and find the nipple when he does not see it. The experiment yields absolutely constant results; if Laurent sees the nipple he brings it to his mouth, but if he does not see it he makes no attempt to turn the bottle over. …Laurent assiduously sucks the wrong end of the bottle.*
>
> *…On the sixth day of the experiment, when the bottom of the bottle was given to Laurent, he looks at it, sucks it (hence tries to suck glass!), rejects it, examines it again, sucks it again, etc., four or five times in succession. Piaget then held the bottle in front of Laurent to allow him to look at both ends simultaneously. Although his glare oscillates between the bottle top and bottom, when the bottom was presented to Laurent again he still tried to suck the wrong end.*
>
> *The bottom of the bottle was given to Laurent on the eleventh, seventeenth, and twenty-first days of the experiment. Each time he simply lifted and began sucking the wrong end. But by the thirtieth day he no longer tries to suck the glass as before, but pushes the bottle away, crying. When the bottle was moved a little farther away, he looks at both ends very attentively and stops crying.*
>
> *Finally, two months and ten days after the start of the experiment, when the bottom of the bottle was given to Laurent he was successful in flipping it over first. He immediately displaces the wrong end with a quick stroke of the hand, while looking beforehand in the direction of the nipple. He therefore obviously knows that the extremity he seeks is at the reverse end of the object.*

Laurent knows how to flip a bottle if he sees the right end, but he continues doing what normally leads to success if he is presented the wrong end. Obviously, what he has to learn, and what takes quite some time, is to link the sight of the bottom of the bottle with the behavioral response of flipping the bottle.

Apparently, Laurent follows a common pattern of learning. He continues to apply a previously successful strategy even if it isn't successful any longer. It is not that he cannot flip the bottle; he knows how to do that. But he does not link the sight of the wrong end with this action. Even showing him the shape of the bottle with the nipple at one end, and the bottom at the other, does

7. J. Piaget (1954).
8. A. Lawson (1995), p. 331.

not help. It takes quite some time and the emergence of frustration to make him stop his normal behavior. Then he is free to look at cues from the situation and try out different types of behavior. Finally, when the act of flipping—which is part of his orienting behavior, or trials—coincides with the sight of the bottom of the bottle, he links the two and from then on uses the new successful behavior. Piaget speaks of a process of disequilibrium being caused by the disappointment of expectations. Individuals then try to reestablish equilibrium. If the process is successful, they have changed: they have truly learned.

### *Fundamental Brain Functions*

How might brain functions explain the learning that took place in young Laurent? We will first look at the fundamental building blocks and functions of the brain. Below we apply this knowledge to building neural network models that mimic the observed learning.

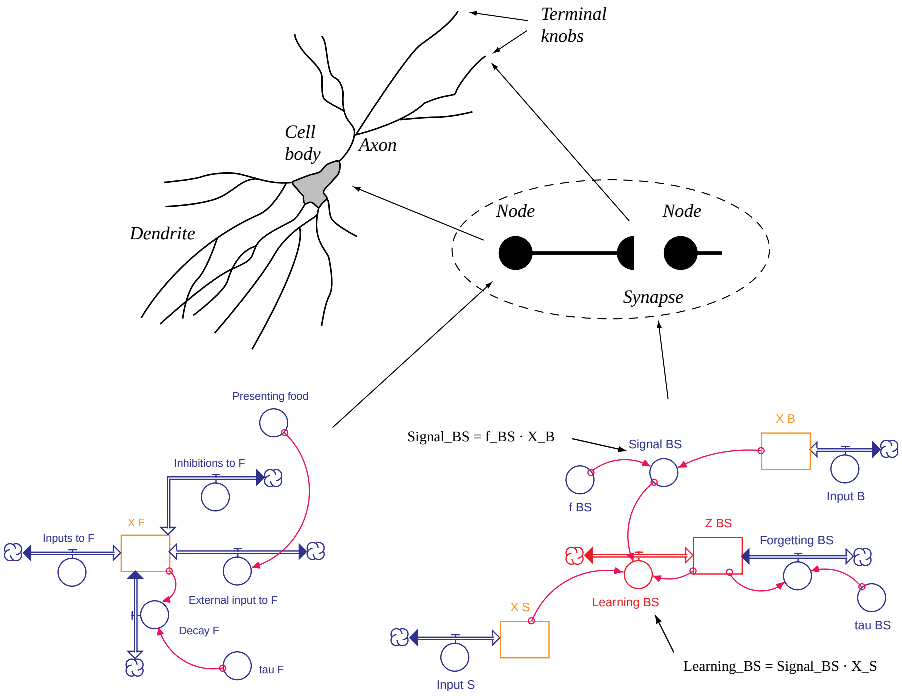


**Figure 1:** Brain cell (neuron) with paths leading toward it (dendrites) and path leading away (axon). The ends of axons connect to the next neurons through synapses. The basic function of neurons and synapses is represented in the accompanying system dynamics model parts. Neurons are the seats of short term memory, synapses are used for long term memory.

A brain consists of cells having cell bodies and dendrites and axons (Fig.1). Dendrites lead signals towards a neuron (from previous neurons in a group or from outside) leading to an excited state (activity) of the cell, i.e., making it fire so that a signal passes down the axon to other neurons. The ends of axons connect to dendrites of the following neurons through synapses. Signals pass the synapses only if these have been conditioned earlier, i.e., if the synaptic strength has been built up sufficiently. This building of synaptic strength is the actual act of learning. Synapses are thought to be the seat of long term memory.

Neurons change their activity as a consequence of different types of signals received from other neurons (both excitatory and inhibitory) or from outside of a group of cells, and due to decay of that state (“forgetting”). Neurons forget relatively fast, so they represent short term memory.

Building of synaptic strength, i.e., learning of the network, works as follows. Two conditions have to be met: first, a signal from the preceding neuron must be travelling toward it, and the neuron following in line must be active. In other words, there must be pre-synaptic and post-synaptic activity for learning to occur. Decay of synaptic strength results in forgetting.

## *Neural Networks*

Neural networks can be constructed from the building blocks just described. The famous example of conditioning dogs to salivate at the hearing of a bell shows how this works. A minimal network that can explain the observation is shown in Fig.2.

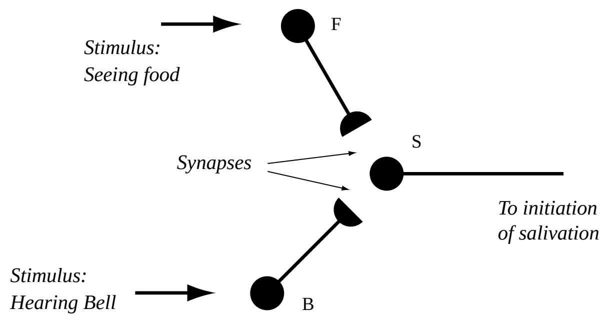


**Figure 2:** Neural network explaining classical conditioning. We need three neurons, one for reacting to seeing food, one for hearing the bell, and one for initiating the process of salivating.

It is assumed that the synaptic strength leading from a neuron receiving input from seeing food to the neuron responsible for initiating salivation has already been built (the dog “knows” to salivate when it sees food). Synaptic strength from B to S (Fig.2) still has to be built. This happens as follows. A bell is rung at the same time as food is presented to the dog. Since the dog sees food, neuron S is active. The animal also hears the sound of the bell, so neuron B is active: the conditions for building synaptic strength at BS are met. Over time, the dog "learns" to salivate when it hears the bell. We say that the hearing of the bell has been conditioned to the response of salivating. Finally, it suffices for the animal to hear the bell to begin salivating; food does not have to be presented.

The learning taking place in Laurent is much more complex than the simple process of classical conditioning. Nevertheless, the case discussed is a building block of more complex neural networks. Here I will describe the last step needed to understand Laurent's change of behavior in some detail.

What is needed is to condition the sight of the bottom of the bottle to the motor response of flipping the bottle (Fig.3). Models of neural networks make use of cells responsible for Nonspecific Orienting Arousal (NOA), cells that randomly initiate different behaviors (looking, searching, moving…). If the NOA responsible for flipping the bottle is active at the same time as Laurent sees the bottom of the bottle, the synaptic strength between the neurons responsible for these two events can be built: Laurent learns to condition the sight of the bottle's bottom to flipping the bottle.

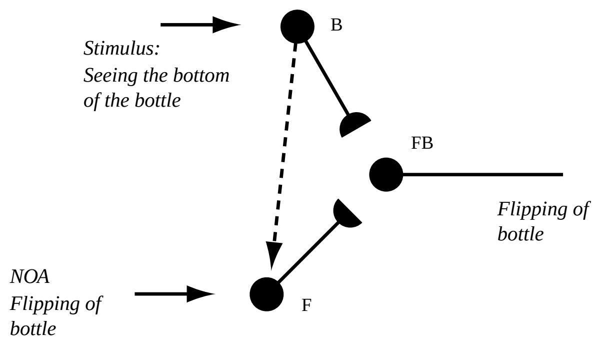


**Figure 3:** Final part of a complex neural network which can explain Laurent's learning. He needs to condition the sight of the bottle's bottom to the motor response of flipping. If Nonspecific Orienting Arousal cells related to flipping are active at the time of the sight of the bottom, the necessary synaptic connection can be built. Turning on of NAO is a response that slowly builds as the result of the unexpected sight of the bottom of the bottle (dashed arrow).

The question here is how the orienting arousal is turned on. Obviously, it is turned off at the beginning: Laurent directly applies his tried and proven behavior of lifting and sucking the bottle (even with the wrong end up). It is believed that the brain uses the process of adaptive resonance. Assume NOA to be turned off at the beginning. An input is compared to a memory, the present is compared to an expectation. If input and expectation agree, NOA continues to be quenched, the input is processed without interruption. If, on the other hand, input and memory do not agree, NOA is turned on and a search in memory is set off until some agreement is found. If none can be found, the sensory input is stored in new cells.

In Laurent's case, NOA should be turned on by the unexpected sight of the bottom of the bottle. Apparently, this does not happen quickly. After all, the previously conditioned response, namely the lifting of the bottle and sucking the nipple, has been very successful. It seems that it can take quite some time for orienting arousal to be turned on under such circumstances. Certain connections in the brain have to be actively removed, while others must be constructed.

### *Consequences*

Cognitive research in psychology and brain research point out general features of learning processes:[9]

- We learn only if our expectations are disappointed.[10] Learning occurs as a result of a persistent mismatch between observation (stimuli) and expectations. The mismatch leads to disequilibrium and a new equilibrium is sought. This process is called self-regulation.
- Just being presented with the right solution does not seem to help the learning process very much.
- Learning is a constructive process: new synaptic connections have to be built. Learning is not a simple inscription of external signals upon an empty but receptive brain.
- Removing old, tried and successful behavior, and replacing it by new behavior, takes time. Turning on nonspecific orienting arousal in the brain does not happen immediately when some unexpected signal is received, at least not if previously successful knowledge or behavior is readily available.

It appears that for successful learning to occur—especially if it requires behavioral and conceptual change—the learner needs experiences that disappoint deeply rooted expectations (initiation of disequilibrium) and time and opportunity to try new behavior and see it becoming successful (establishment of a new equilibrium).

If I take these clues seriously, the question presents itself of how I can implement learning processes that provide the necessary experiences for the learner.

9. Ashcraft (1994), Lawson (1995).
10. Schank (1997).

Let me briefly come back to the question stated in the introduction: do we need new concepts before we can change behavior, or do we have to learn to change our processes and as a consequence we are ready to accept new concepts? I stated that I think that the latter is true. Now, this may be a chicken and egg question. Very likely both processes, both changes, have to occur in parallel. Still, I believe it helps to think in terms of behavioral change as being fundamental, especially in this information age. Moreover, there is good reason to think of knowledge and thinking not so much as just information and information processing in an otherwise inactive individual. There seems to be a very tight connection between thinking and acting. Hans Aebli called thinking the "putting of order into our actions."[11] Simply stated, we think in order to be able to act, or to improve upon our actions.

## 3 LEARNING CYCLES

Learning is a constructive process, not a simple inscription of new information into the brain. The brain changes old synaptic connections and constructs new ones. This happens when the learner is allowed to go through phases of disequilibrium initiated by the disappointment of expectations, which must be followed by the establishment of new equilibrium resulting from trying new paths and seeing them become successful. How can we construct learning processes that provide the learner with what seems to be necessary?

### *The Scientific Process*

How is science performed by professionals? Can we learn from how physics knowledge is constructed? If thinking means putting order into our actions, we should try to learn to think by engaging in action. Rather than being to difficult for the beginner, the process of doing science harbors the steps necessary for successful learning.

First, it is important to realize that science does not progress in a direct line from observation to concepts and theories by way of induction. Induction allows us to organize and categorize our observations, nothing more. It is true that science receives its cues from nature, but our ways of making sense of objects and processes do not follow from the observations. Rather, we create ideas or hypotheses. The process leading to the formation of hypotheses is called abduction. It is like an input from the outside, or from a different "dimension," making use of analogical reasoning.

Once hypotheses are generated, they are tested. This works as follows. We derive consequences

11. Aebli (1980).

of our assumptions in the form of "If…then…" statements. These are compared to our observations or experimental results. As long as tests of our hypotheses lead to positive results, we retain the assumptions and eventually build them into formalized structures called "theories."

What has been said here about the progress of science has some deep similarities with the learning processes described earlier. Remember that learning is not a direct inscribing of information from the outside into our brains, just as science is not a direct consequence of observation. Rather, our brain compares incoming information to existing patterns in the process called adaptive resonance—an act like the one where we compare consequences of theories to observations. The use of analogical reasoning in hypotheses building reminds me of the search for pattern matching in the brain. Progress in science results from what we do when we are surprised because our expectations (the consequences of our ides) do not match with the input from reality.

If all of this is true, we should try to give learners the opportunity to engage in activities and processes that are similar to those found in fundamental scientific reasoning. In essence this means that students should get to explore reality, be encouraged to form ideas about why things work the way they do, and be invited to compare the consequences of their ideas to what they find in the real world.

## *The Learning Cycle*

In the early 1950s and 1960s, Karplus and Chester Lawson[12] independently introduced what became known as the learning cycle in science teaching. They stressed that instruction should lead students from exploration, through invention or term introduction, to concept application or discovery (Fig.4).

These stages form a cycle, or rather a spiral, as we pass through them several times as we build our knowledge of nature. In a circle, there is no obvious beginning. Studies of science learning, however, indicate that it is important to start an investigation into a field or subject by first engaging in the exploration of phenomena. This is quite different from many course formats where teachers begin by telling students about the conceptual or formal basis of a subject. The less experience students have with the objects and processes of the field of study, the more important it is to let them develop the vital overview before we subject them to the task of sense making. Once that task has been accomplished by building and testing hypotheses, students should get a chance to see their ideas in action by trying them on related examples. As summarized by Chester Lawson[13], learning should involve:

12. Karplus and Thier (1967), C. Lawson (1958); see A. Lawson (1995).
13. C. Lawson (1967).

- attention to some undifferentiated “whole”
- the differentiation of the whole through identification of its parts
- the invention of a pattern by which the parts are interrelated
- testing the invented pattern to see if it applies
- use of the pattern in other similar instances.

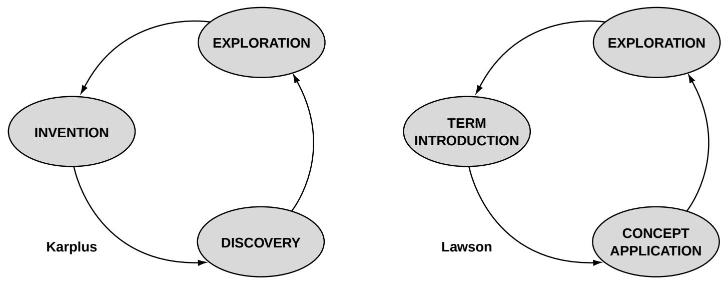


**Figure 4:** The learning of science can be organized according to the Learning Cycle developed by Karplus and Lawson. Exploration should precede the introduction of terms or the formation of ideas as a second step. Ideas, concepts, or theories should be applied to phenomena similar to those that stand at the beginning of the investigation.

The essence of the most advanced form, so-called hypothetical-deductive learning cycles, has been described by Anton Lawson:[14]

> *…This allows the possible creation of alternative conceptions and misconceptions with the resulting argumentation, disequilibrium, and analysis of data to resolve the conflict. …they call for the creation and explicit testing of alternative hypotheses to explain a phenomenon. In brief, a causal question is raised, and students must propose alternative hypotheses. These, in turn, must be tested trough the deduction of predicted consequences and experimentation. …The resulting arguments and analysis of evidence represents a near-perfect example of how hypothetical-deductive learning cycles can be used to promote disequilibrium, the construction of conceptual knowledge, and the development of procedural knowledge.*

Learning that makes use of the learning cycle is hard to envision in a traditional classroom or lecture hall setting.[15] I believe that it requires at least a very large proportion of active engage-

14. Lawson (1995), p.143-144.

ment time, measured as a fraction of total time spent learning a subject. Active engagement learning according to the learning cycle or similar approaches are called inquiry based learning processes. Currently, inquiry based science learning is advocated by major groups involved in formulating science education policies.[16]

The sequence of exploration, concept development, and application is quite intuitive. It remains to be seen, however, how each stage can be put into practice. When we consider this question we will recognize that the learning cycle of Karplus and Lawson is more like a hyper-cycle where each stage consists of basic cyclic activities.

### *An Example from Heat Transfer*

Before I go on to answer the stated question, I shall present an example of the investigation of simple heat transfer.[17] In terms of the learning cycle, assume that we are at stage one (exploration, in Fig.4). Here is a suggestion for a sequence of activities.

- Students get an opportunity to study a number of different experimental setups and processes which exhibit important aspects of heat transfer. The study is largely qualitative.
- Students describe the observations, i.e., they answer the question of "how" the processes run.
- The students are asked to give reasons for what they have observed, i.e., they should begin to answer the question of "why" the processes run as observed. They should try to construct so-called mental models (qualitative models) or first hypotheses. Finally, students should list the principles they are able to detect in their ideas (reflective action).

In this form, stage one of the learning cycle already contains what Lawson would call term introduction (Fig.4), and what I call (mental) modeling. However, a detailed concept construction has not occurred yet. This is left to stage two of the learning cycle:

- Now, a number of concrete predictions should be made (for example, what happens

15. Actually, elements of activity oriented learning can be, and have been, implemented in large physics lectures. See Mazur (1997), Sokoloff and Thornton (1977).
16. National Research Council (1996), American Association for the Advancement of Science (1986).
17. This unit assumes that students have already worked on some thermodynamics. Specifically, I let students investigate thermal phenomena first with the aim of developing a qualitative understanding of entropy (heat) and temperature, and of the relation of entropy and temperature to energy. Then, students are exposed to the heating of liquids to find their temperature-entropy relations, warming factors, and entropy capacitances (classically, one would introduce the specific heats which relate to energy rather than to entropy). See Fuchs, Ecoffey, and Schütz (2001).

to the initial rate of change of the temperature of water in a can if the water is cooler than in a first experiment?).

- Experiments are planned and prepared to allow for the predictions to be compared to reality.
- The experiments are performed, results are recorded.
- Experiments and predictions are compared.
- In a guided tour students are led to build the concept(s) behind heat transfer: heat transfer depends upon the temperature difference between fluid and environment, the surface area of the container, and the physical properties of the heat transfer layers from the fluid to the environment. Finally the students are asked to compare the principles constructed to the ones they listed after their first modeling activities (reflective action).

Now we go on to the stage of application in the learning cycle sequence. Students are given the following assignments:

- Study the cooling of water in a thin-walled sealed aluminum container (such as a polished beer can). The water is stirred continuously. Record the temperature of the water and of the environment. Present and describe the results.
- Analyze the system; in particular, list the processes undergone by the water.
- Create a (system dynamics) model of the cooling of water in a thin-walled can.
- Simulate the model. Introduce the data taken in the experiment into the model and compare the simulation results to the data taken.
- Use the comparison of reality and model to find values of physical parameters (heat transfer coefficient, etc.).
- If a satisfactory agreement cannot be reached, decide if you need additional experimental runs or altogether different experiments to answer some questions; or
- change the model and repeat the steps of simulation and comparison.

Students do not have to stop at a single application of the principles constructed in stage two. Depending on the subject and the time and the resources available, several applications of the type described here for stage three can be envisioned.[18]

Already at a first glance we see that there are at least two major types of activities required of

18. The complete chapter of introductory thermodynamics in the Integrated System-dynamics Learning Environment described below (Fuchs, Ecoffey, Schütz, 2001) again makes use of the learning cycle structure. Stage one corresponds to an investigation of phenomena including the construction of qualitative concepts of entropy and temperature. Stage two consists of several sections which introduce the elements needed to model simple thermal processes. At the end, in stage 3, some small projects are presented.

the investigator: modeling and experimenting. In my interpretation of the three steps or stages of the Karplus-Lawson learning cycle, they all are composed of the same activities, possibly in a slightly different order or with changing emphasis.

### *The Modeling and Experimental Bi-Cycle*

An analysis of the steps and activities proposed for the stages of the learning cycle reveals a simple underlying structure. There are two groups of activities—modeling and experimenting—which are joined together by the act of comparing their results, and by decisions made as to how to react to possible discrepancies and surprises (Fig.5).

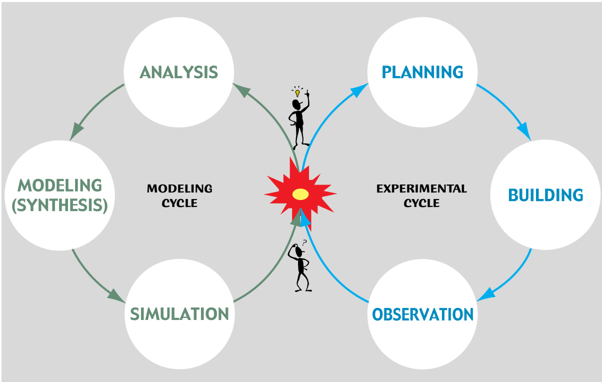


**Figure 5:** The details of the scientific process can be represented by two interrelated cycles. Science develops by creating models (hypotheses, theories) whose consequences are compared to reality, or what we can see in reality through experiments and observations. Each of the cycles consists of a sequence of steps which allow the learner a relatively easy orientation. Note the similarity of the bi-cycle with the description of learning by C. Lawson (1967) given above, and with design processes in industry.

Either one of these groups forms a cycle by itself. For this reason I call the result a bi-cycle or double cycle. Since it combines modeling and experimenting, we may as well call it the M&E Bi-cycle. Sometimes I refer to it as the project cycle or the design cycle since projects in the sciences and design projects in industry pretty much use procedures like the ones described here. In industrial design, modeling and prototype building combine to a practical and time saving method for designing new products, or for optimizing existing products and processes.

The modeling cycle may be broken down into analysis, modeling, and simulation. The border between analysis and modeling is not sharply delineated. Analysis may refer to the first steps in which we “take apart” a situation or system to gain more clarity. In the field of dynamical systems,[19] this means choosing an object or control system and thinking about and identifying the processes occurring. In mechanics we would try to find the momentum flows exchanged between the object and the environment, in a thermal application we have to identify all entropy flows and entropy production rates. Once we have come this far we can start to synthesize or "build up" a model from our knowledge of the processes identified. Whether or not we take the formulation of the special laws for the processes to be a part of analysis, or already of model building, does not really matter. In the end we arrive at a dynamical model which can be simulated, i.e., whose equations can be solved. Fundamentally, working out consequences of assumptions or hypotheses in one's head is the act of simulating a (mental) model.

Experimenting can likewise be divided into steps. I commonly identify planning, building, and observation. Observations lead to the data needed for the comparison of nature and our models (hypotheses). Whether or not we gain the data from an experiment or from simply observing existing objects (like stars in astronomy), does not matter. Planning and building in the case of pure observations means planning what we want to observe and building the necessary tools to perform the observations.

Some crucial aspects of working and learning with the bi-cycle and the learning cycle do not seem to get the necessary space and attention in the forgoing description and in Fig.4 and Fig.5. I am referring to the act of comparing observations and simulations, reality and model, or nature and our hypotheses. There is an icon showing where the two sides meet in Fig.5. But how is the comparison really performed? Or more importantly, what are the conclusions drawn from the comparison, or how do we arrive at conclusions? In the most fundamental sense, the conclusions are new or modified hypotheses or models, or decisions concerning new experiments. Remember what I said about constructing hypotheses. It appears that input from outside of the bi-cycle and the learning cycle is necessary to generate new ideas. Analogical reasoning seems to be the means by which we arrive at hypotheses. Obviously, my picture of the bi-cycle in Fig.5 does not yet contain a theory of how the ideas for models are created or constructed. This is still an unanswered question for me.

## 4 INTEGRATED LEARNING ENVIRONMENTS

The preceding conclusions give solid advice about how learning might be structured and organized, but the question remains of how and where I can actually implement the learning cycle with its components, i.e., with modeling and experimenting. As discussed before, I find it difficult to imagine how I could construct full fledged learning cycles in a lecture hall. Having ac-

19. Fuchs (1996, 1998, 2002)

cess to a lab to accommodate a usually small part of the total teaching does not make the situation much better. In my experience, lectures and labs do not integrate to form a unit in the heads and minds of my students.

The use of learning cycles and the M&E Bi-cycle leads to inquiry based learning in a setting that allows active engagement. I do not believe that letting students watch me create models on the computer or demonstrating experiments to them can have more than a minimal effect. It is like trying to learn to swim or to play the piano in a theory course. Therefore, I envision a physical setting for a real learning environment that can house the learners and the tools they need for their learning. The best environment that comes to my mind at this point is a studio. Artists and architects learn in studios, so why shouldn't my students when they work on physics? In fact, the idea of studio learning in physics, mathematics, or engineering is not new. I have seen implementations of it at Rensselear Polytechnic Institute[20] in Troy, New York, and I have heard of other studio settings for physics learning.

### *An Integrated System-dynamics Learning Environment*

A studio containing all the necessary tools and learning materials for a physics course that makes use of the learning cycle and the modeling and experimental by-cycle is an integrated learning environment. Because I employ explicit system dynamics modeling I call it an Integrated System-dynamics Learning Environment (ISLE). The environment integrates the different methods, procedures, and activities that form the core of science learning. Specifically, it unites system dynamics modeling[21] with experimenting. Concept development is expected to be a result of the activities.

Two years ago I first used materials for a short unit on introductory thermodynamics developed by Georges Ecoffey, Edy Schütz, and myself in a studio setting.[22] The class of about 24 students was divided into two groups which worked in a small lab equipped with desktop computers, some experiments, and data acquisition tools. Two researchers accompanied the month-long trial run.[23] Last year I improvised three introductory units on hydraulics, electricity, and

20. Wilson (1994).

21. I have not said much about system dynamics modeling—or modeling in general—except that it is an essential element of the M&E bi-cycle and gives the activities of hypothesis building, prediction, and test of predictions, a clear profile. This may create the impression that (system dynamics) modeling is no more of a problem than, say, using basic mathematics in a physics course. This is true to a certain extent. There are user friendly and powerful tools, and there exists ample evidence that even young students can successfully create and work with system dynamics models (Forrester, 1998-). Still, like any other skill, the application of system dynamics modeling needs to be developed. My students have trouble interpreting graphs, or manipulating data, or planning an experiment. So why should this be different with the art and science of modeling? See Fuchs (1998) or Fuchs (2002) for more details on system dynamics modeling in physics.

22. Fuchs, Ecoffey, and Schütz (2001).

rotation before using the thermodynamics unit again. We are still working on analyzing student feedback from this trial.

My students' inexperience with inquiry based learning, and my inability to adequately stress process over content, combined to make the experience only partly satisfactory. In general, my students were happy with being exposed to a practical way of learning, and they see a great potential in this type of learning environment. Moreover, their formal learning was at least comparable to what I am used to from previous years—in spite of the fact that I drastically reduced the amount of classroom teaching or lecturing (from 80% of contact time down to about 20%). But I concur with their judgment that I am still a long way from properly implementing the learning cycle approach. Specifically, I have not yet reached what I now see as a central goal: that the new problem solving approach—explicit modeling—must turn into a successful experience for them—replacing their old but ineffective behaviors. Much still remains to be done.

Are integrated and inquiry based courses expensive? Actually, this does not have to be so at all as evidenced by studio learning at Rensselaer Polytechnic Institute.[24] In that format students in groups of about 40 receive four weekly contact hours. This is compared to the previous setup of two hours of a large enrollment lecture, two hours of lab plus two hours of recitation. The cost of the new course compares to the old one, while its success with students is higher.

### *Virtual Learning Environments*

People put much hope into virtual learning environments these days. So do I, if they are fashioned after real environments and make use of what we know from research into learning and teaching. Since good materials are required in an ISLE for the phases of independent investigations, and since much of the learning of physics makes use of computers anyway, I decided to create a Personal Virtual ISLE. The idea is to have interactive materials ready for personal study at home and for group study in the studio. The materials are expected to recreate much of what students can find in a real environment:

- guidelines for investigations;
- experiments: pictures, movies, descriptions, real data;
- virtual experiments for extended "experimentation;"
- tools for data analysis and presentation;
- models and modeling tools;
- texts, figures, graphs, animations, tables, examples, etc., for concept development and formal study.

23. Ernst and Fuchs (2001).
24. Wilson (1994).

The materials on CD[25] are—or will be—accompanied by a textbook. So far I have been using Chapter 5 of Borer et al.[26] for the part on introductory thermodynamics. Again, as in the case of the real environment, the challenge has been to create an environment which allows students to engage in inquiry based learning using the learning cycle and the M&E bi-cycle. The same criticism leveled at the real environment has been voiced against its virtual counterpart: it still has to meet its true promise. In addition, much care has to be exercised in making virtual materials user friendly. It is all too easy to get lost in cyber-space, ruining the potential of such learning materials.

### *Collaborative Distance Learning Environments*

Materials for virtual learning environments and communication tools make another approach to learning possible. Students can join in collaborative activities from home for distance learning or as a part of their normal studies. An example of collaborative learning, the CoVis project for collaborative visualization,[27] has been developed and tried for several years already. Visualization of data is an important element of certain fields in the sciences and makes activity based versions of study possible and exciting. For the future, I envision the same happening to modeling and simulation. However, apart from a short trial run where colleagues at the University of Karlsruhe and I created a small model using Stella[28] over the Internet, I have not been able to do much in this regard yet. I believe, however, that the activity of joint model development can serve as a prime integrating element for groups of students learning together at a distance.[29] If it is true that students should be active if possible when studying in a real learning environment, I cannot see that this should be different for virtual and distance learning.

## 5 PHYSICS EDUCATION RESEARCH AND BEYOND

Reform in physics teaching and learning, both in high school and at the introductory college level, has made great strides in recent years. Based on research in physics education, several groups have published materials that have one thing in common: they stress activity based learning beyond what we have been used to from classical text books.[30] Companies are provid-

25. Fuchs, Ecoffey, and Schütz (2001).
26. Borer et al. (2000).
27. Collaborative Visualization project at North Western University (1998).
28. Stella (system dynamics modeling software): High Performance Inc. Hanover, New Hampshire. There are several other similar tools on the market.
29. Combine CoVis with CoEx (Collaborative Experimentation) and CoMod (Collaborative Modeling) and you have all the elements necessary for implementing the M&E bi-cycle.

ing data acquisition materials that make the laboratory a modern interactive work place.[31] Just as important for me have been the developments in the didactics of system dynamics modeling and simulation,[32] the physics of dynamical systems,[33] and, least but not least, the creation of computer and Internet based interactive materials, including some for collaborative activities.[34]

Physics education research[35] has had and is continuing to have an important influence upon recent developments and innovations in teaching and learning. Let me just mention a few keywords which show the breadth and depth of the problems investigated. Computer based materials necessitate intelligent tutoring systems.[36] Cooperative Group Problem Solving[37] is an attempt to put more activity based learning into the standard problem solving approaches, and to include problem solving in innovative designs such as studio teaching.

It has transpired in recent years that learning can be aided considerably if students are made to reflect upon their activities. Approaches have been designed that ask students to reflect upon their learning by asking questions such as “What did I learn? How did I learn it? What remained unclear?” and answering them in weekly reports.[38] The weekly reports have been used as part of a novel physics learning environment that uses the same acronym as our project ISLE: Investigative Science Learning Environment.[39] This environment shares many crucial elements with what we have been designing here in Winterthur and in Fribourg. In the words of the authors of the Investigative Science Learning Environment:

> *[Investigative Science Learning Environment] is a learning system that helps students learn physics using the same strategies that physicists use to construct their knowledge. These strategies include using experimental evidence for knowledge construction and model building and testing. Students … design investigations and constantly reflect on knowledge construction. …They work in groups and learn to communicate with each other. …When combined [these elements] produce a unique combination called ISLE.*

Obviously, our subject is ripe for harvest.

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30. Sokoloff, Thornton, and Laws (1999), McDermott (1996), Linn and Hsi (2000).
31. Vernier; Pasco.
32. Forrester (1998-), Fuchs (2002).
33. Maurer (1990), Fuchs (1997a).
34. See for example the Web Physics Project or Just in Time Teaching (JITT).
35. See for example the PER Supplement to the American Journal of Physics.
36. Reif and Scott (1999).
37. Cummings, Marx, Thornton, Kuhl (2001).
38. Etkina (2000), Etkina and Mills (2001).
39. Etkina, Brahmia, Zou, Van Heuvelen (2001).

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