SYSTEM DYNAMICS MODELING IN FLUIDS, ELECTRICITY, HEAT, AND MOTION

Examples, Practical Experience, and Philosophy

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Abstract: System dynamics provides for a general and user friendly approach to the modeling of dynamical systems, irrespective of the field of application. Although SD modeling – as it is practiced in areas from economics to ecology – is hardly known in physics and physics education, physics is particularly suited to the methodologies and tools of system dynamics and systems thinking.

In this talk, examples of modeling and the direct comparison to experimental data will be discussed. Examples range from simple (draining of a tank, heating of a body, charging capacitors, muffin cups falling in air) to larger case studies (the circulatory system of mammals, thermoelectric cooling). The examples have been developed for and used in introductory university physics for engineering students.

As described here, SD modeling is an element of an integrated learning environment where experiments, modeling, and simulation blend with the learning of the formal aspects of our science. The talk describes practical experience gained with this type of learning environment in recent years.

Finally, it will be demonstrated that SD modeling suggests how the use of analogical reasoning can be made into a major tool for learning an abstract field such as physics. It will be shown that the analogies used in fluids, electricity, heat, and motion are based upon fundamental human reasoning. Evidence of this reasoning is found in conceptual metaphors used by humans in everyday life.

1 INTRODUCTION

Modeling is the name of the game in physics, and Newton was the first system dynamicist. If we look at modeling in physics at this granular level, we do not really need a conference on modeling in physics (or physics education). Whenever we do physics, we model. So what else is there to say?

It does make sense, however, to look at modeling in physics more specifically from at least two points of view. One, there are different types of models and, consequently, there are different ways of modeling. Second, modeling is not dealt with explicitly in most of our classrooms, so it will be worthwhile to discuss methods that let us deal with modeling in an explicit form in physics education—even at a very early stage in the education young people.

System dynamics modeling is special in some well defined ways and it is easy and powerful enough to lend itself to explicit modeling in the classroom (traditional, lab, or studio). In fact, it is so easy and powerful that it may well be one of the best tools and methods to effectively integrate modeling with experimental activities in a way that reflects important aspects of the scientific method. Again, tools and methods are applicable even at an early stage of the educational enterprise.

The Origins of System Dynamics Modeling

System dynamics was not developed with physics in mind. In the US, most practitioners of what has become known as system dynamics call themselves members of the social sciences. True, system dynamics, as it was developed by Jay Forrester, has its roots in control engineering, cybernetics, and systems science in general—which in turn have their roots in early systems science in biology and physics. But today, most of the activity going on in system dynamics proper is indeed found in the social sciences, and maybe in environmental science. Donella Meadows wrote in 1991 (Meadows, 1991, p.1):

> *"System dynamics is a set of techniques for thinking and computer modeling that helps its practitioners begin to understand complex systems—systems such as the human body or the national economy or the earth's climate. Systems tools help us keep track of multiple interconnections; they help us see things whole."*

An Example: Natural Gas Usage in the USA

Here is an example of a diagram representing the visual elements of a model of natural gas usage in the US during the 20th century (Roberts et al., 1983, Chapter 23); see Fig.1. Note the main structures outlined in solid color. It represents two *laws of balance*, one for the quantity of gas believed to be (left *Undiscovered*) in the Earth's crust, and for the *Reserves*, i.e., the quantity of gas discovered and placed in the "virtual container" of known reserves. Laws of balance are first order differential equations (*initial value problems*). The first storage element is depleted by the process of discovery, the second is replenished by this process, and depleted by usage (which basically is the same as the production rate). The quantity labeled *Discovery* is the rate that "moves" gas from the one container to another. The process quantities *Discovery* and *Usage* are determined by feedback relations expressing our ideas of how these processes work. These relations are so-called *constitutive relations* that express the differences and variability found in various systems. Laws of balance, in contrast, are always of the same form; they are the *generic laws* of a model.

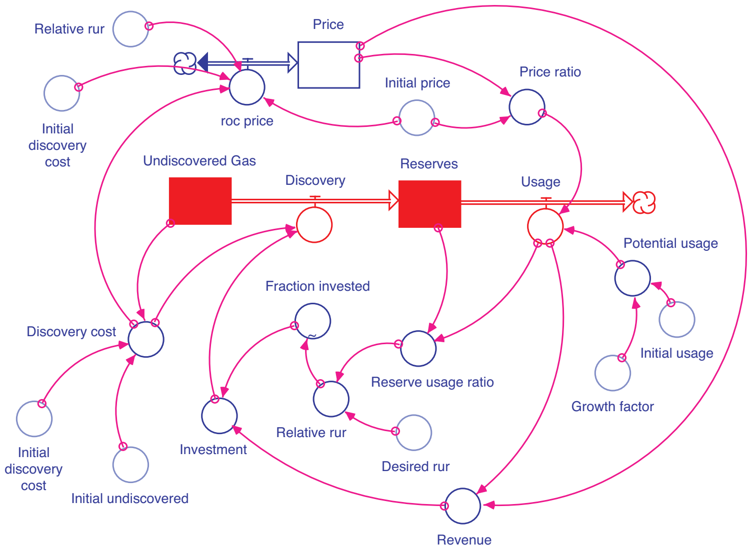


Figure 1: A model representing the use of natural gas. Note the different elements. Rectangles (called stocks) represent stored quantities, pipelines (called flows) symbolize processes (flows or production rates). Combinations of stocks and flow in general represent laws of balance (solid color at the center of the diagram). There is a stock-flow structure which is not a law of balance. The relation between Rate of Change of Price and Price is a simple integrator. The relation that matters is the "inductive" law that determines a rate of change of price based on some "pressures." The process quantities are determined by feedback relations expressed by circles (variables) and thin connectors. See Fuchs (2002), CBT Chapter 2, p. 96-115.

Note that there is another structure made up of a storage symbol (*Price*) and a flow symbol (*Rate of Change of Price*). This is not a law of balance. Rather, nature—or economics—determines the rate of change of *Price*. (The structure made up of stock and flow serves to integrate the rate of change to yield the proper quantity.) We are accustomed to thinking of inflation as the result of inflationary pressure which determines how fast prices change. In physics, such a relation is equivalent to an inductive phenomenon (a pressure difference determines the rate of change of a current).

A model of the type shown in Fig.1 can be simulated, and the simulation results can be compared to data. The comparison yields important information about the quality of the ideas underlying the model (Fig.2).

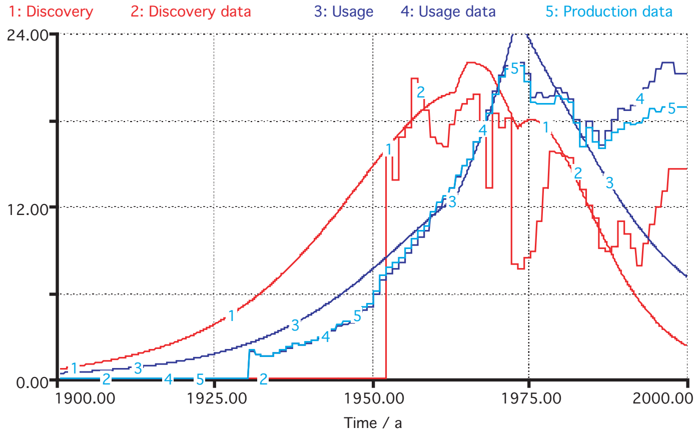


Figure 2: An example of a simulation of the model shown in Fig.1, and a comparison of the simulation (rounded curves) with data (jagged curves). Discovery rates and usage rates are shown. After about 1980, usage and production rates start to deviate.

In summary, system dynamics modeling applies a graphical approach to building models of dynamical systems by combining the relations we perceive to hold in such systems. It makes use of very few structures which are projected onto virtually any type of dynamical system and its processes, i.e., it makes strong use of *analogical reasoning*.

Mathematically speaking, the models created are initial value problems of spatially uniform elements.

SD Modeling Tools

We use modern graphically oriented tools to produce evolution equations; the tool should make use of containers and flows (and production rates), and auxiliary quantities (and integrators).

There are several programs available that implement the SD approach. The earliest tool that included a full-fledged graphical interface was Stella. A similar tool sporting somewhat more sophisticated numerical methods is Berkeley Madonna.

2 EXAMPLES OF SD MODELS OF PHYSICAL PROCESSES

Physical systems and processes can certainly be part of the complex dynamical systems Donella Meadows talked about (see Section 1, Meadows, 1991). Moreover, they provide us with some of the simplest systems upon which a successful introduction to SD modeling and systems science can be based. The practice of SD modeling, together with the development of continuum physics (Fuchs, 1996) and the didactic approach to physics developed in Karlsruhe (see Herrmann, 1991-1995), inspired me to look for a generalized, "system dynamics friendly" representation of basic physical processes, and to use physics to guide our view of the general structure of system dynamics models (Fuchs, 2002a). In the following, I shall present some examples of models and their comparison to experiments. The applications have been developed for a first year university physics course for engineering students.

Two Communicating Oil Containers

Communicating fluid containers represent one of the simplest and most basic systems that can teach us much about the modeling of dynamical processes (Fig.3).

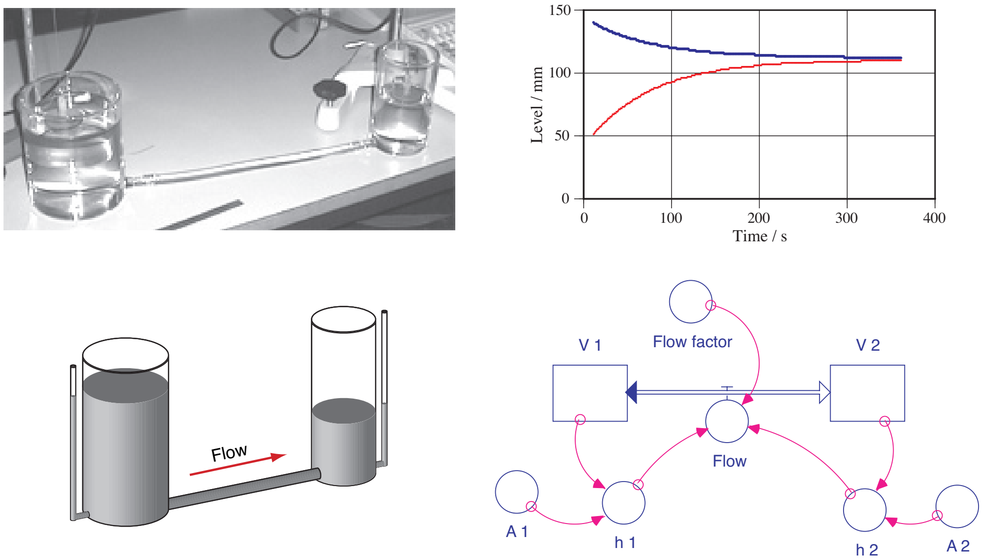
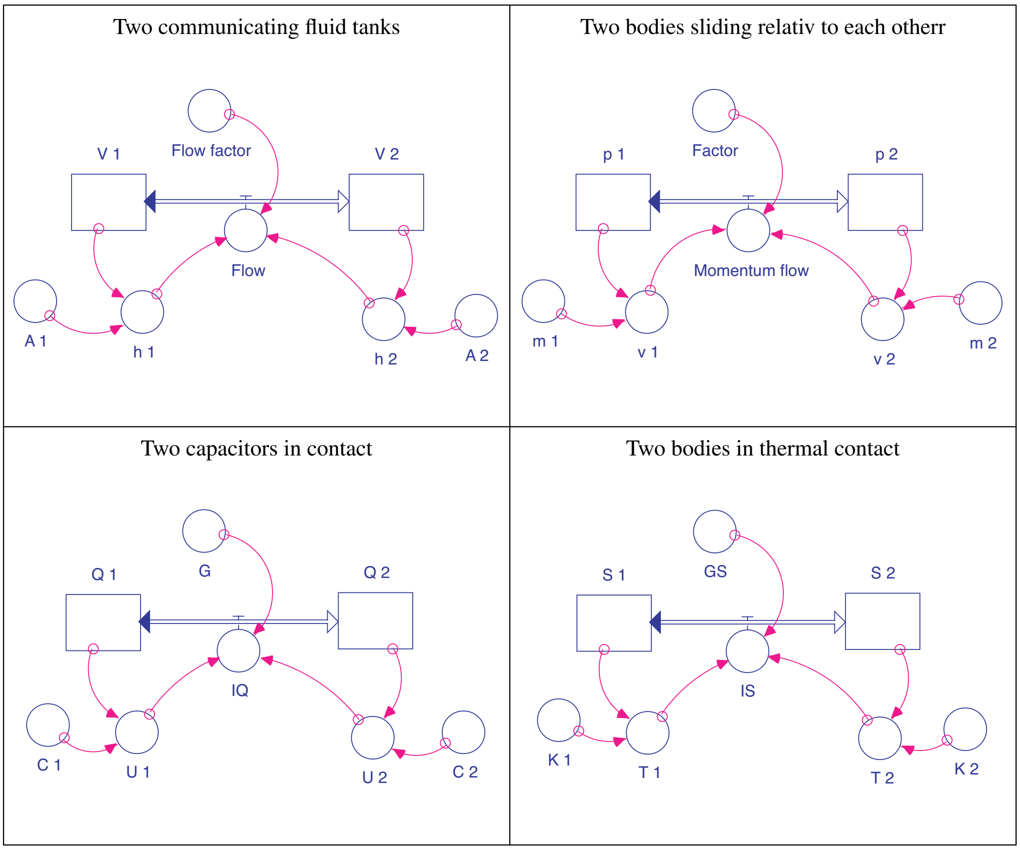


Figure 3: Two communicating oil tanks (top left), data of the equilibration of levels (top right), situation sketch (bottom left) and SD model diagram (bottom right).

The diagram of a system dynamics model of two communicating fluid tanks is built around the laws of balance of fluid volumes in the two tanks (Fig.3, bottom right). The volumes of fluid change as a result of the flow of oil from the container having a higher oil level to the one having a lower level. The flow is assumed to depend upon the difference of fluid levels. In the simplest case, the flow is proportional to this difference. Using these assumptions, the model yields close to perfect agreement with experimental data.

A Comparison of Equilibration Processes in Fluids, Electricity, Heat, and Motion

The simple structure of a model of communicating oil containers can be transferred to all the other basic physics processes (Fig.4). The equilibration of fluid levels, velocities (translational motion), voltages (electricity), and temperatures (thermal phenomena) can be explained using analogous structures. In the thermal case, there is a problem though (see the next sub-section).


Two communicating fluid tanks

Two bodies sliding relativ to each otherr

Two capacitors in contact

Two bodies in thermal contact

Figure 4: The phenomena of the equilibration of fluid levels, voltages, velocities, and temperatures can be explained with the help of analogous model structures.

Entropy Transfer and Entropy Production

The comparison of simulations and experimental data is successful for the examples shown in Fig.4, with the exception of the model for thermal equilibration. This model applies to a system where two liquids at different temperatures are in thermal contact. The liquids have constant entropy capacitances (such as in the case of glycol). We know from experience that the final temperature reached by two equal amounts of glycol is higher than the average of the initial temperatures. The model, in contrast, predicts the average value of the initial temperatures.

The reason for the limited success of the simple model in Fig.4 (bottom right) has to do with the fact that we have neglected entropy production due to dissipation. As in all conductive transfers, energy is dissipated and entropy is produced as a result. Whereas entropy production does not influence the balance of amounts of liquids, charge, or momentum, it certainly changes the balance of entropy in entropy transfer between two bodies in thermal contact (Fig.5). More entropy flows into the colder body than leaves the warmer one. In conductive entropy transfer, energy is released and dissipated. Entropy production is a result of this dissipation.

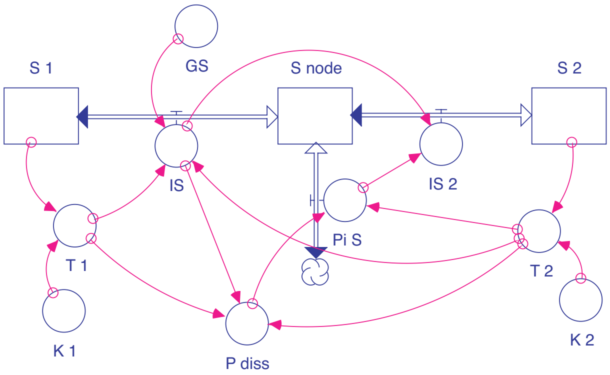


Figure 5: If entropy flows conductively from one entropy storage unit to another, entropy is produced (think of a thermal resistor between the two storage units). Here, a stock has been introduced to represent a node (junction) that does not store entropy. The junction rule relates the entropy current out of storage unit 1 (IS), the entropy production rate (Pi_S), and the entropy current into the second storage unit (IS_2). The entropy production rate is determined by the ratio of the dissipation rate and the (lower) temperature. The dissipation rate equals the rate at which energy is released in the fall of entropy from T1 to T2 (this quantity is calculated from Carnot's relation).

A comparison of a model of two bodies of water in thermal contact inside an insulated double container with real data shows that the inclusion of entropy production makes the model successful (Fig.6). If we turn off the effect of entropy production in this model, there is a small but noticeable difference between simulation results and reality.

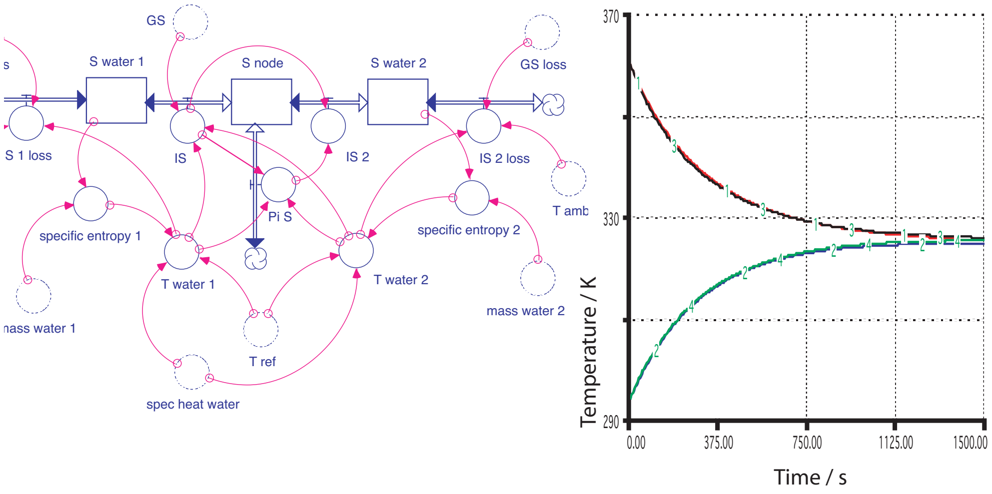


Figure 6: Model, simulation, and data, for two bodies of water in thermal contact inside an insulated container having two compartments separated by a thin metal wall. The model makes use of the irreversibility of conductive entropy transfer. Here, the expressions for the entropy-temperature relation have been adjusted to the case of water (constant specific heat means an exponential *Ts*-relation).

Inductive Effects in Fluid Flow: Blood in the Aorta

Pressure and blood flow change rhythmically inside the aorta of a sheep. A fairly successful model can be built by using the structure of Fig.3. The aorta is divided into small sections (elements) and for each element the pressure is calculated from the volume of blood stored. Blood flow between two adjacent elements results from the pressure difference between these two parts. At one end we have the heart as a pump, at the other end we add blood flow through a long pipe symbolizing the vessels through the body. We get fair agreement between simulated and measured blood pressure, but there is an important difference between model and reality for blood flow.

In reality, there is a small back-flow of blood in the aorta (negative volume currents) for part of a cardiac cycle. This phenomenon cannot be explained with the model structures used so far. Combinations of *RC* elements do not lead to oscillating currents.

The solution is found by adding the effect of hydraulic induction to the model (between each element of the aorta, Fig.7). A part of the pressure difference between two elements leads to time rates of change of the currents of blood. The SD structure that deals with this phenomenon is similar to the combination of stock and flow used to calculate changing prices in an economic model (see Fig.1).

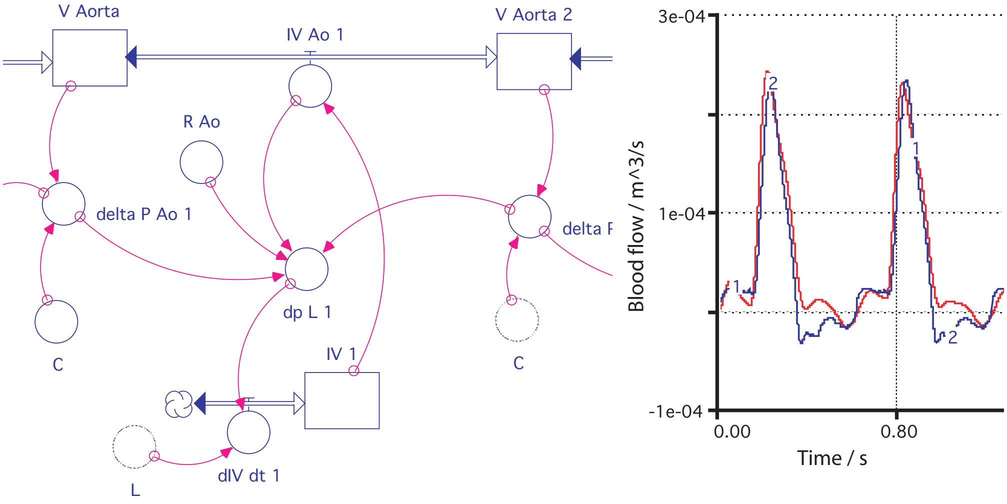


Figure 7: If inductive (inertial) effects are included in the model of blood flow, the current is obtained from integrating the rate of change of the current (lower stock-flow relation). The rate of change of the current results from the inductive pressure difference which is the difference between the (driving) capacitive pressure difference (delta_P_Ao_1 – delta_P_Ao_2) and the resistive pressure difference (equal to R_Ao·IV_1 for laminar flow). Even though the comparison between data (blue) and simulation results (red) is less than perfect, we get the desired result of oscillating currents.

Thermoelectricity: A Peltier Device

To conclude this list of examples, I will discuss a simple model of a thermoelectric Peltier device. Such a device can be run as a generator (heat engine) or as a heat pump. Seen from a distance, the device appears to operate as follows. There is always a hot side and a cold side, and a side that is at a high electric level whereas the other side is at a low level; in other words, there are thermal and electrical “tensions” or driving forces across the device. Obviously then, currents of entropy and of charge go through the device from one side to the other.

Observations show that a temperature difference sets up an electric driving force (thermoelectric voltage). If we model the electric properties as two capacitors representing the sides of the Peltier device at high and at low potential, respectively, there must also be something like a generator element between the capacitors. The electric phenomena can therefore be models as in Fig.4 (bottom left) with an additional thermoelectric voltage driving the current between the capacitors.

The thermal system is made up of two thermal capacitors (entropy storage elements) with two types of entropy transport: One, the standard conductive flow from hot to cold sides and two, a forced current which is coupled to the electric current (Peltier effect). Without this current we cannot explain how one side of the device can become cold at the expense of the other. The SD model of the thermal aspects therefore looks like the model in Fig.5 with an additional—non-dissipative—entropy current (Fig.8).

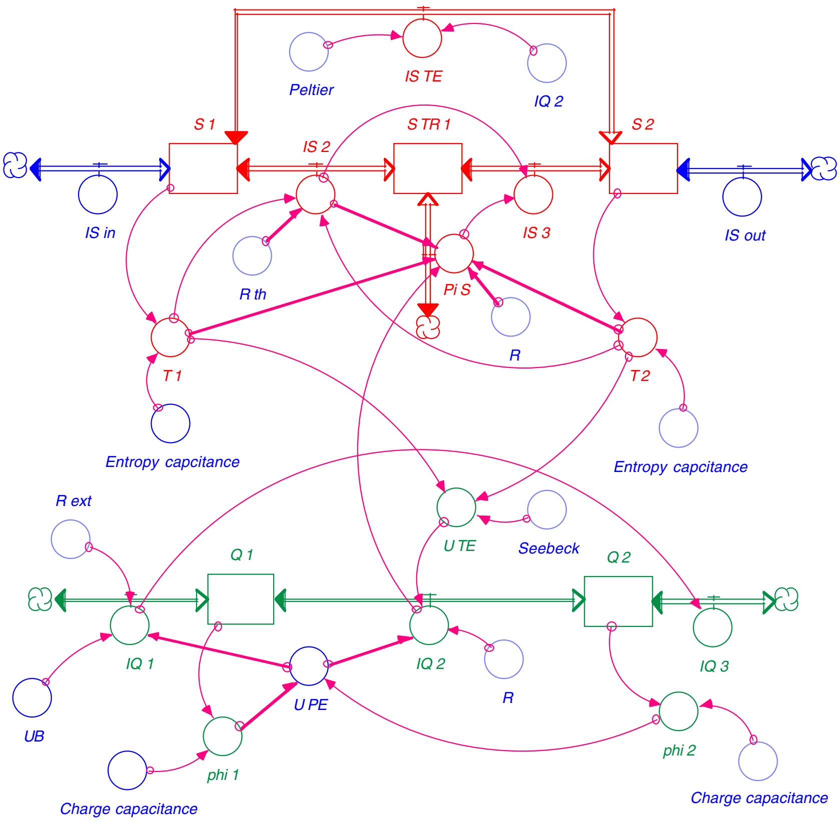


Figure 8: Model structure of a Peltier device. Thermal and electrical aspects are modeled as seen in previous examples (Fig.4 and Fig.5). What makes the device work are the couplings between the two phenomena. Note the relation between electric current and (Peltier) entropy current, temperature difference and thermoelectric voltage, and conductive flows and entropy production.

The thermal and the electric side are coupled; there are three feedbacks. First, the temperature difference produces the thermoelectric voltage which is part of the drive of the electric current between the electric capacitors. Second, the additional (Peltier) entropy current is proportional to the electric current. Third, the electric current leads to an additional entropy production—in addition to that resulting from entropy conduction.

The factors relating temperature difference and thermoelectric voltage one the one hand, and between electric current and (Peltier) entropy current on the other, must be equal. It is interesting to note that we can prove this based on continuum physics arguments (Fuchs, 2002b). If we calculate energy relations we see that the balance of energy will be violated if the Seebeck and Peltier coefficients are not equal.

Structure of SD Models in Physics

So what can we learn from the examples about the structure of system dynamics models of physical processes? And what does this tell us about how humans "see" nature? The second question will be dealt with in Section 4.

The models have at their centers combinations of stocks and flows which are expressions of laws of balance for quantities such as fluid volume, electric charge, entropy, momentum, angular momentum (for rotation), and amount of substance (for chemical processes). These quantities accumulate, and they can be changed as a result of flow and production processes.

Processes are related to differences (of potentials). We can interpret potential differences as driving forces that lead to flows, production rates, and changes of flows. These differences are in turn produced by differences in storage elements and pumps (in a generalized sense; a battery is a pump for electricity).

When quantities flow through a difference, energy is released. The energy released is used to drive other processes (set up other differences), dissipated, and/or stored.

The image emerging here closely corresponds to what we know from continuum physics. System dynamics models of the type presented above are spatially uniform versions of continuum models. They lead to a unified presentation of the most basic physical processes of the following form (Fuchs, 1996, p. 2; see also Fuchs, 1997a, 1997b, 1998):

> *First, we have to agree on which physical quantities we are going to use as the fundamental or primitive ones; on their basis other quantities are defined, and laws are expressed with their help. Second, there are the fundamental laws of balance of the quantities which are exchanged in processes, such as momentum, charge, or amount of substance; we call these quantities substance-like. Third, we need particular laws governing the behavior of, or distinguishing between, different bodies; these laws are called constitutive relations. Last but not least, we need a means of relating different types of physical phenomena. The tool which permits us to do this is energy. We use the energy principle, i.e., the law which expresses our belief that there is a conserved quantity which appears in all phenomena, and which has a particular relationship with each of the types of processes.*

3 MODELING IN AN INTEGRATED LEARNING ENVIRONMENT

The examples of system dynamics models and the experiments they are based upon were developed in and for an integrated learning environment. Modeling activities are integrated with experimental work and form the backbone of the learning process. The areas covered are taken from the physics of dynamical systems (fluids, electricity, heat, substances, and motion). This learning environment is used in first year university courses for engineering students. One of the aims is to confront the students with aspects of systems science.

The Modeling-Experimental Bi-cycle

The interaction of modeling with experimenting can be symbolized as a bi-cycle (Fig.9). Each cycle represents a sequence of activities having to do either with modeling (analysis, model construction, simulation) or experimenting (planning, building, measuring, data processing). When modeling leads to a simulation result, and experimenting yields sets of data, these results can be compared. The comparison typically suggests how to proceed with further work. We may want to improve upon the model, perform more and other experiments, or both. In other words, the bi-cycle is a visual model for a form of the scientific method.

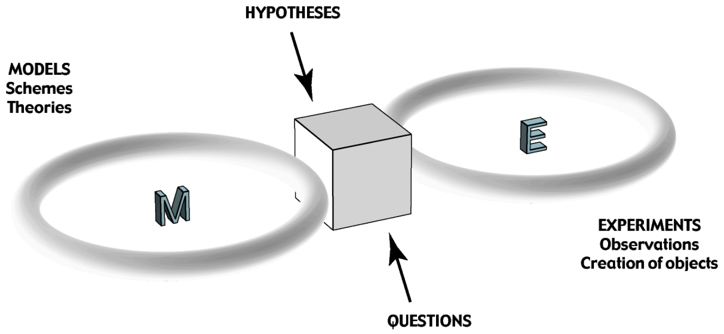


Figure 9: Bi-cycle representing modeling (left) and experimenting (right). The interaction of these activities is symbolized by the cube at the center.

Note that in this relatively standard and traditional view of the scientific method, two important elements are missing. Where do good questions for investigation and hypotheses for models come from? The problem of hypotheses will be discussed in Section 4.

Contents, Tools, and Materials of the Integrated Learning Environment

Choosing to base a physics course on the bi-cycle in general, and on the modeling of dynamical processes in particular, will surely lead to changes in a typical introductory physics course. The decisions made here lead to a course that is based upon the continuum physics paradigm (Fuchs, 1997a) and integrates physics with systems science (Fuchs, 2002a).

The models presented are part of a curriculum that is best described as leading to applications in chemical and energy engineering, environmental science, biology and medicine. These fields provide us with important and fascinating systems that are different from traditional applications in physics in their relative complexity. They are worthy of an approach that leads learners toward an appreciation of dynamical systems and systems science. Typically I work on most of the ten subjects shown in Table 1 in a 12 credit first year course for engineering students. An important aspect of the learning environment is the inclusion of case studies with each of the subjects. Case studies motivate the physics, and they allow me to stress methodological aspects such as stressing the scientific method by going repeatedly through the bi-cycle (Fig.9).

Table 1: Themes and Case Studies[a]

	Subject	Case Study
1	Storage and flow of fluids	The systemic blood flow of mammals
2	Electric processes and energy	Supporting batteries by superconductors
3	The dynamics of heat	Thermoelectric cooling
4	Chemical processes	Stratospheric ozone
5	Induction, oscillations, waves	Diodes and chaos
6	Rotational mechanics	Keeping time: Mechanical clocks
7	Translational motion	Parking space craft at Lagrange points
8	Heat, fluids, and radiation	Atmosphere, radiation, and winds
9	Flow systems	Latent heat storage
10	Dynamical systems	The inverted pendulum

a. Fuchs, Ecoffey, Schuetz (2001-2006).

The materials that support the learning environment are made up of texts, movies and data presenting experiments, models, guides, problem sets, and more. They are implemented on DVD and can be accessed through a standard browser.

A number of tools are needed to work actively on physics problems and case studies. They include data acquisition, spreadsheet software, system dynamics modeling programs, and the Internet.

Experience with the Integrated Learning Environment

The experience gained over the last four to five years makes me hopeful that activity based learning of physics in an integrated studio environment is a viable alternative to standard physics courses based on the lecture-recitation-lab approach. Dynamical modeling takes a larger role than in any other studio course I am aware of. It has by now become an indispensable element in a course that allows students to work on real-life applications (in fact, allows them to let learning be guided by these applications). Intuition for and qualitative understanding of the most important physical principles are developed quite naturally as a consequence of the activities. Students consistently remark that they like the systems science approach based on the explicit use of analogies.

4 IMAGINATION, FIGURATIVE THOUGHT, AND SD MODELING

We tend to believe that propositions in physics are basically independent of the human mind. They are out there in the world, ready to be “found” by scientists. In other words, they are objective and “true” representations of the (material) world existing outside of us. One consequence of this is that physicists are inclined to accept physical theories in the form in which they were developed in their time. They seem to forget that physical theories are models, that physics is a model. Theories are a creation of the human mind that makes use of all the figurative forms of thought upon which human reasoning was built through evolutionary history.

Recent work in cognitive science gives us a radically different picture. Human reasoning is figurative—rooted in imaginative structures—through and through (Johnson, 1987; Gibbs, 1994). Some of the most interesting work on figurative structures has been done in cognitive linguistics (Lakoff and Johnson, 1980, 1999; Lakoff, 1987; Gibbs, 1994). This research demonstrates how we can make use of human language—by investigating conceptual metaphors—to understand how humans “see” the physical world around them. Recently, I have identified some of these structures (Fuchs, 2005). Interestingly, they have much in common with models of physical processes found in continuum physics. To some degree, the metaphors are built into the system dynamics tools that were developed in recent decades.

Above, I described the bi-cycle as a standard model of scientific methods (see Fig.9) and mentioned that it lacks in two important respects. Two questions remain unanswered: How do people come up with good questions for investigations, and where do ideas for models come from? Our typical reaction to these questions is “…and then Einstein (Newton, Maxwell…) had an idea…” In this section, I would like to show that the human power of generating ideas and hypotheses for models (of physical processes) stems from imaginative structures that are visible in conceptual metaphors with which all of us describe nature.

Where do ideas for models come from?

Generating ideas for hypotheses is thought to be a highly creative act. Since we are moving in largely uncharted territory, we often attribute this type of creativity to only a few special individuals. Based on the theory of cognitive tools (Egan, 1988, 1997, 2005) I would like to argue that every human has access to tools that allow them to be creative in the sciences in an important sense. We can specify acts of thinking and working much like in the case of modeling and experimenting that allow us to come up with good questions and ideas for models. Therefore, I have extended the bi-cycle of Fig.9 to a quadruple-cycle (Fig.10). Two new cycles symbolize some (fairly) concrete steps we can take when confronted with the "soft" tasks of generating good questions (motivation) and ideas for hypotheses. I identify the acts with two cognitive tools described by Egan (2005) which he calls *mythic* and *romantic* thinking. Suffice to say that Egan has concrete suggestions for what constitutes these forms of human thought.

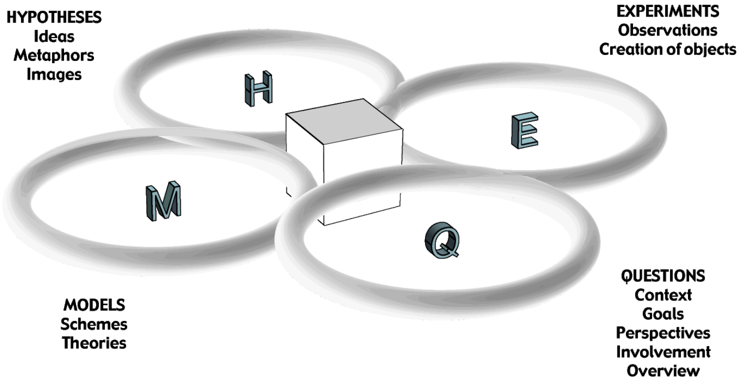


Figure 10: The bi-cycle of Fig.9 is extended to a quadruple cycle by including the cognitive tools of mythic and romantic thinking for answering questions regarding the generation of hypotheses and questions.

In my model, the generation of ideas and hypotheses (the cycle H in Fig.10) is associated with mythic thinking. Mythic societies are those that use oral language only. Orality leads to some interesting cognitive tools that demonstrate aspects of imaginative structures of the human mind such as metaphoric reasoning (Ong, 1982). This has led me to a search of conceptual metaphoric structures in physics that might tell us where to look for the roots of ideas and hypotheses for physical processes.

Conceptual Metaphors

Metaphors are traditionally called embellishments of language used by gifted writers or speakers. We go so far as to think of metaphor as the antithesis to “true” literal expressions: Metaphor is “not real” and even “lies.” Recent work in cognitive linguistics informs us that metaphor is not so much a linguistic expression than a form of thought—in fact, a fundamental imaginative structure upon which human reasoning is based (see Kövecses, 2005, for a recent textbook on conceptual metaphor). A conceptual metaphor such as *Organizations are Plants* has many (linguistic and other) expressions such as “The company grew strongly,” “The branches of the firm,” or “Their recent efforts bore fruit,” etc. Conceptual metaphors have entailments which represent examples of how we reason based on the metaphoric structure. Conceptual metaphors are essentially unconscious, and when they are made conscious we often do not recognize them as such. They lead to such inconspicuous expressions as “The temperature is high,” “Electricity is flowing,” or “The force of water.”

The Gestalt of Physical Processes

My personal experience with students’ reasoning and research into the origins of thermodynamics (Fuchs, 1996) lead me to believe that we experience (classes of) physical processes as gestalts. Experience with collectives of phenomena that lead to a perception (such as phenomena having to do with fluids, or with hot and cold) are abstracted so that they become a perceptual gestalt—a gestalt of fluid substances, of electricity, of heat, of chemicals, or of motion (see Fuchs, 2005).

Gestalts are wholes that are more than the sum of possible parts. (The term *gestalt* can mean “pattern” or “configuration.” In gestalt psychology it is emphasized that the whole of anything is different from the sum of its parts: Organisms tend to perceive complete patterns or configurations rather than bits and pieces. See King and Wertheimer, 2004) Gestalts are normally undifferentiated. However, when we ask people to describe their experiences of the sum-total of a class of perceptions (such as thermal ones), their words tell us that we do see aspects in a gestalt—the gestalt appears to be weakly differentiated. Most interesting for our purpose here is that the aspects associated with different gestalts seem to be basically the same. And this holds for physical as well as completely non-physical examples (consider the concept of pain).

The aspects identified (unconsciously) are (1) *intensity*, (2) *substance*, and (3) *force* or power. Here is an example. We speak of quantities of electricity, electricity can be strong (intense) or weak, and there obviously is a force (power) of electricity. Clearly, the same structure emerges in other classes of phenomena as well. Wiser and Carey (1983) have identified exactly this type of image in the reasoning of the Experimenters of the Accademia del Cimento (1667) applied to thermal phenomena. Carnot’s analogy of water and heat is a result of reasoning based on the same gestalt—in explicitly differentiated form of a modern scientific theory (Carnot, 1824; Fuchs, 1996). And if we analyze our language concerning general abstract concepts such as love or pain, the same general gestalt having the same aspects can be discerned.

Metaphors for the Aspects of the Gestalt of Physical Processes

The aspects of the gestalt of a physical process are structured metaphorically. In fact, the third aspect is so rich that it constitutes its own gestalt with its own set of metaphors. The conceptual structures of these aspects are

1. Intensity is structured in terms of the metaphoric projection of the up/down image schema (schema of *verticality*) onto the concept in question. (See Johnson, 1987, on image schemata.) Examples: High speed, temperature rises, low pressure, higher voltage…
2. The amount of something is metaphorized as a *fluid substance*, where fluid substance is again an image schema. Examples: Electricity flows, momentum is transferred, heat has been stored, substance is produced, more liquid…
3. Force or power is related to the gestalt of direct manipulation. In other words, this concept has to do with how humans perceive and conceptualize causality. The gestalt of direct manipulation has been described by Lakoff and Johnson (1980, p. 70):
   - There is an *agent* that does something.
   - There is a *patient* that undergoes a change to a new state.
   - Properties 1 and 2 constitute a single event; they overlap in time and space; the agent comes in contact with the patient.
   - Part of what the agent does (either the motion or the exercise of will) precedes the change in the patient.
   - The agent is the *energy source*; the patient is the *energy goal*; there is a *transfer of energy from the agent to patient.*

The meaning of the first two is clear to physicists. The first leads to the concept of potential (intensive physical quantities) whereas the second serves to conceptualize extensive (additive) quantities as substance-like. The form of the third aspect of the gestalt of a typical physical process—that of force or power—suggests that it could be the source of our concept of energy. The relation between extensive and intensive quantities and energy is well-known from continuum physics (Eringen, 1971-1976; Müller, 1985) and from Gibbs' thermodynamics (Falk and Ruppel, 1979; Callen, 1985). Carnot (1824) expressed this relation succinctly for the first time in dynamical form. There is a visual metaphor that expresses what he meant, the metaphor of the waterfall. In his book, *The Motive Power of Heat*, he wrote:

> *According to established principles at the present time, we can compare with sufficient accuracy the motive power of heat to that of a fall of water … . The motive power of a fall of water depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used,*

> *and on what may be termed, on what in fact we will call, the height of its fall, that is to say, the difference of temperature of the bodies between which the exchange of caloric is made. In the fall of water the motive power is exactly proportional to the difference of level between the higher and lower reservoirs. In the fall of caloric the motive power undoubtedly increases with the difference of temperature between the warm and the cold bodies; but we do not know whether it is proportional to this difference.*

It seems to me that the differentiation of the three aspects of the gestalt reached a first level of maturity in Carnot's work. This, and the strong use of analogical reasoning, led to a form of a thermodynamic theory which still serves as a model for how we can most easily understand the concepts of continuum physics, and as a consequence, of the physics as it transpires through the use of system dynamics modeling presented here.

Visual, Verbal, and Mathematical Expressions of Metaphors

If metaphors are structures of thought, they can be expressed in different ways: Through mimesis (Donald, 1991), visually (Arnheim, 1969), linguistically, mathematically… I will briefly discuss visual metaphoric expressions. Linguistic ones have been described above. At this point I cannot yet specify possible mathematical expressions of the metaphors identified here. The challenge of how to see images in equations might prove quite interesting for physics didactics. Mathematics is metaphor based, that much is clear (Lakoff and Nunez, 2001), but how this translates to our challenge I do not yet know.

A set of diagrams has been developed to express the elements of the gestalts discussed above, and the relations between these elements (see Fuchs, 1996, 1997a). The diagrams make use, among others, of the waterfall image created by Carnot. For our present purpose, however, the metaphors contained in typical system dynamics tools are of more immediate interest.

The examples presented before in Section 2 show that three types of reasoning are supported by *visual expressions of underlying metaphors*. They are

- Substance-based thinking: Made evident by stocks and flows.
- Causal thinking: Visualized with the help of combinations of stocks and flows (single stocks, and interactions between stocks).
- Feedback thought: Expressed with the help of the thin connecting lines leading (more or less directly) from stocks to flows.

This corresponds to some extent to the structure of the gestalt and its apsects discussed above. The image schema of verticality and the gestalt of the waterfall (as a symbol of the power of a process) are not as visible as we might wish from the viewpoint of physics.

It appears to me that we should not underestimate the intelligence expressed by the creation of maps by hand or at the computer screen. The graphical user interfaces of system dynamics programs are more than mere gimmicks.

Roots of Analogies

I shall present a particular view of the origin and nature of analogies as they are constructed in continuum physics. In this view, a clear difference between metaphor and analogy emerges.

In general, metaphors are projections of a source domain onto a target domain (Fig.11). The metaphor *Organizations are Plants* projects our understanding of plants onto that of organizations. According to the nature of the source and target domains, one speaks of different types of metaphors. For our purpose, the simplest type of metaphor is of interest: The projection of an *image schema* onto a target domain. Image schemata are recurring structures of or within our cognitive processes which establish patterns of understanding and reasoning. They emerge from our bodily interactions, linguistic experience and historical context. They are some—if not *the*—most basic structures of human understanding (Johnson, 1997, Chapter 5).

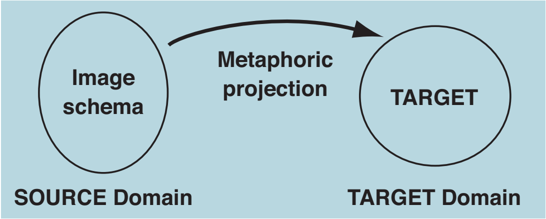


Figure 11: A metaphor is a one-sided projection of a source domain onto a target domain. A particularly primary form of metaphor results from the projection of image schemata.

It has been pointed out above that the first two aspects of the gestalt of physical processes (intensity and amount or substance) are structured metaphorically on the basis of the image schemata of *verticality* (for intensity) and *fluid substance* (for amounts or substance). In other words, we have, at minimum, two basic metaphors for a field of experience.

If different phenomena in the physical world are abstracted as the same type of gestalt having essentially the same aspects, the same image schemata are projected onto all of the classes of phenomena—fluids, electricity, heat, substances, and motion—alike (Fig.12). Take heat and electricity, for example. Both are metaphorized based on the schemata of verticality and fluid substance. In physics we create the concepts of temperature and entropy, and of electric potential and electric charge, respectively, as measures of the aspects of intensity and of amount of heat or electricity.

As a result of identical metaphoric structuring, thermal and electric phenomena obtain a degree of similarity. They can now be compared and lend themselves to an analogy, a mapping of structure from one to the other, and back. Metaphors are two-sided projections of structure from one (previously) structured domain onto another (Fig.12).

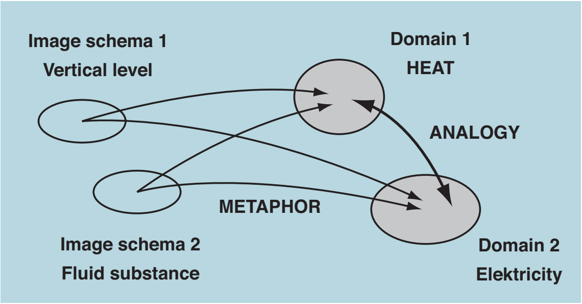


Figure 12: Analogies are made possible based on similarity of two structured domains. The similarity is the result of equal metaphoric structuring of each of the domains. The mapping is (more or less) symmetrical.

Naturally, the structuring of the domains of fluids, electricity, heat, substances, and motion also includes the aspect of force or power. Here, an entire structured domain—the gestalt of direct manipulation—is projected onto a sum-total of experience (such as heat or electricity). In physics, the structure of this gestalt is rather simple: Carnot's waterfall image basically says it all. The power of a process depends upon the quantity of the fluid substance flowing through a level difference. It is proportional to both,.i.e., double the current of the fluid substance or double the potential difference leads to double the power. Again, the domains of fluids, heat, etc., are analogous in this respect.

Most important for the further development of a subject is the following observation. Metaphors—the metaphoric projection of knowledge from one domain onto another—leads to *entailments*. We can reason about the target domain based upon the properties of the source. Take the example of the fluid substance. The fact that (real) fluid substances obey a law of balance can be directly transferred to the substance-like quantities of physics.

Continuum Physics and System Dynamics modeling

It is quite clear from the foregoing that continuum physics has the conceptual metaphoric structure outlined in this Section. As a consequence, system dynamics modeling of physical processes does as well since it models the spatially uniform subset of continuum processes. SD modeling obviously makes use of a successful form or human reasoning.

5 SUMMARY

In summary, let me list some aspects of system dynamics modeling that might be important for the learning of a science such as physics. The first observation is that SD modeling is simple. The tools are learned easily. More importantly, by simple graphical procedures, we create formal structures that are commonly thought to be quite advanced, i.e., systems of initial value problems.

Second, system dynamics modeling is interdisciplinary. In physics, it allows us to treat fields such as fluids, electricity, heat, chemical processes, and motion in a strongly analogous fashion. We know why the methodology is so successful: It makes use of a fundamental form of human reasoning as evidenced by its metaphoric structure.

Third, modeling of dynamical processes using these modern tools is practical and powerful. It lets us integrate experimental and modeling activities quite easily. It supports the scientific method and serves as an integral tool in design procedures.

Finally, it supports the creative mind since it is “natural” in an important way. SD modeling reflects (at least some) fundamental aspects of figurative human thought. It is close to a full representation of the gestalt and its aspects which humans see in natural processes. The metaphoric projection of the same image schemata onto diverse phenomena makes these phenomena similar. As a result, fluids, electricity, heat, substances, and motion lend themselves to the application of analogical reasoning.

Finally, let me add that some high school physics courses do make extensive use of the structures discussed in this paper. The first is the extensively applied and researched Karlsruher Physikkurs (Herrmann, 1989-1999), the second is a course introduced in Switzerland that makes explicit use of system dynamics modeling (Borer et al., 2005).

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