The Continuum Physics Paradigm in physics instruction

I. Images and models of continuous change

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ABSTRACT: An introductory college physics course has been designed, implemented, and taught for several years which combines the continuum physics paradigm with systems thinking and system dynamics tools for modeling and simulation of dynamical processes. In short, it provides an explicit general modeling strategy applicable to all fields of physics and even to fields outside of this science, allowing for student centered (learner directed) learning. The fundamental ideas of continuum physics can be cast in the form of a simple graphical image which is borrowed from the flow of water at the surface of the Earth, and which can easily be translated into system dynamics models of processes. This unified approach to physical processes significantly revises the standard model of physics courses, adds an important methodological dimension not commonly used in physics instruction, and places physics beyond its own borders together with other sciences, engineering, and social studies. It makes use of phenomenological primitives, and it deals with, and proposes a practical solution to, conceptual problems identified in standard courses over the last few decades.

This first paper in a series of three describes the basis of the continuum physics paradigm, lists important problems to be solved, discusses its implementation in physics instruction, outlines a possible curriculum, and looks at the future of physics instruction. The following two papers describe important aspects of the approach—system dynamics modeling, and the nature of a dynamical theory of heat (including steps toward the teaching of continuum physics).

I Introduction and overview

For the last 10 years, Werner Maurer and I have been designing and teaching a new calculus based introductory college physics course.[1–3] It derives its motivation from the Continuum Physics Paradigm (CPP) and makes use of system dynamics modeling. We are now in a position to give an account of the structure and the logic of the approach. In this introduction we will discuss our motivation for the project, and give a brief overview of the most important issues. In the following two papers (which will be called CPP II and CPP III, respectively), important aspects of the approach will be discussed—system dynamics modeling in physics instruction, and the nature of a dynamical theory of heat.

Why redesign the Standard Model of Physics instruction? The last two or three decades have seen the growth of interest in educational research, and many changes to what might be called the Standard Model (SM) of introductory college physics have been proposed or implemented. Cognitive research has given us new insights into how students think;[4] new instructional techniques have been developed,[5] supported by new materials and new computational tools;[6] and the content matter of the SM has been questioned because of the neglect of quantum physics.[7] However, the SM has survived the developments fundamentally intact; it still serves as the paradigm of how physics is to be presented or, more precisely, of how we are supposed to understand nature. In short, even though the content matter of most of the SM is classical macroscopic physics, particles, forces, and trajectories dominate our view of nature.

While we have been strongly influenced by recent developments in physics instruction, our central motivation for redesigning the Standard Model derives from a different set of observations. We believe that the time has come for a significant change of what—and how—we teach. These are some of the reasons:

- Our view of nature and of our own role in it has changed profoundly. More than ever before we see all of nature as a vast dynamical system—like an organism. This view calls for new concepts and tools for learning. Physics has to join the other fields of human inquiry and help to create a unified approach to the world around us.
- On a smaller scale—within physics itself—it is time for a unification of (classical) phenomena and subjects. We cannot keep claiming a leadership role within the sciences if physics presents itself as a relatively loose collection of different concepts and theories for each field.[8]
- During the last three decades, a general science of the dynamics of heat was developed[9]—as opposed to a theory of the statics of heat. Recently, this theory was transferred to introductory physics.[3]
- The subject of dynamical systems has added new and exciting opportunities to research in physics, and the field has led to new insights.[10]
- More than 50 years ago, a general science of systems grew out of physics, biology, and engineering.[11,12] Today we have tools for systems analysis which are not only powerful but also very simple to use.[13] They could easily change the way we learn and teach the sciences, engineering, and social sciences.[14]
- Teachers have learned about the negative impact of students' conceptions of nature which make learning more difficult.[15] Since we need a paradigm to be able to state what constitutes a misconception, different views of nature may lead to different answers to this question; some representations of fields of physics may themselves be the source of misconceptions.[16] We believe that—in some of the most important aspects—the CPP is closer than the SM to our everyday view of how nature works.[17,18]

These are powerful challenges for physics instruction. If we accept some or all of them, we are called upon to reevaluate the SM. It turns out that continuum physics can serve as a unifying principle for much of physics instruction.

Central issues of the CPP approach and of physics instruction. If we wish to base physics instruction on a new paradigm we have to deal with the new issues which will certainly arise. We identify five main challenges:

- Considering that continuum physics is known as a complex and mathematically demanding theory, how do we introduce its fundamental ideas at the beginner's level?
- How can we deal with dynamical systems at an early stage in physics instruction?
- How will the concept of energy be included in the generalized approach of the CPP?
- How can we present a theory of the dynamics of heat to beginners?
- What are the sources and forms of possible misconceptions in the CPP approach?

These challenges have surprisingly simple solutions. The view of nature developed in continuum physics[19] can be cast in the form of a simple yet powerful image (Section II) which makes use of laws of balance (Section III). We view physical processes as the result of the flow, production, and storage of certain additive quantities such as charge, entropy, momentum, amount of substance, and so forth. This image can be translated into models of dynamical systems with the help of systems thinking and system dynamics tools which require little sophistication for initial successful application (Section IV and CPP II). The solution of the third problem makes use of a graphical interpretation of the role of energy in physical processes first proposed some twenty years ago[20] which relates the additive quantities and energy (Section V). The challenge of thermodynamics so far has led to a proposal for how to transfer continuum thermodynamics to a beginner's level.[3] It uses the thermal law which is equivalent to Newton's law in mechanics in dynamical form—the law of balance of entropy. If we take the CPP view of nature serious, the introduction of entropy in a beginner's course is simple (Section II and CPP III). Finally, students' conceptions of nature, and their influence on learning, have been the focus of interesting and important research in recent years.[15,21,22] A critical analysis of students' beliefs in, for example, mechanics and thermodynamics indicates that our everyday notions are closer to a continuum physics image than to the one created by particles and trajectories.[16-18] This issue has been and will continue to be a guiding concern during our design of the new physics course (Section VI).

Continuum physics appears to have little in common with quantum physics. Therefore, we could justly ask if we are not moving away from what is often taken as the most important challenge in physics instruction today: how to include quantum physics in the Standard Model. Since the basic quantities of the CPP are precisely those which play a fundamental role in quantum physics, we believe that we are even closer to the physics of this century than in the SM. This opens up new avenues for investigation.

Implementation and results. Werner Maurer and I have been designing and implementing the CPP approach step by step over the last 10 years. For some years now we have had a fairly clear understanding of a subset of the approach. This part which we call the Physics of Systems I (PS I) deals with spatially homogeneous systems (Section VII). We have been teaching this part during the first year of introductory physics instruction in the departments of mechanical and electrical engineering at Technikum Winterthur. The last two major elements added in this development were the inclusion of a system dynamics modeling lab (CPP II), and the conclusion of the theory of the dynamics of heat in analogy to the other fields of the PS I approach (CPP III).

Teaching physics in this manner has brought noticeable changes in the education of engineering students, particularly in the fields of mechanics, energy and chemical engineering, and control engineering. Our colleagues tell us that students deal much more easily with advanced modeling problems than just a few years ago. Moreover, we have been able to motivate students to do project and thesis work in fields involving considerable amounts of applied physics and mathematics.[23] Also, in the last couple of years we have been teaching courses for high school teachers who have become interested in transferring our approach to their instructional practice. Moreover, a course taught in junior high school, the Karlsruhe Physics Course,[24] demonstrates that the basic ideas can be used just as well with rather young students.

Outlook. In the PS I subset which deals with fluids, electricity, heat, and motion, we model phenomena as spatially homogeneous. This allows us to use the full power of the system dynamics approach. Naturally, this brings up the question of what to do about spatially extended systems—bodies, fields, and waves. So far, we have found it easy to teach these subjects along the lines of the Standard Model, simply building on the concepts acquired during the first year. However, we are not completely satisfied with this approach. In particular, thinking of the growing interest in modeling of spatially extended systems in engineering and the natural sciences, we hope to be able to develop a similarly rigorous modeling theory as for the simpler spatially discrete case.

What a system dynamics approach does not do. The PS I subset does not cover every aspect of the physics of macroscopic systems. In particular, there is one field of inquiry which is not touched directly—geometry. In other words, where geometrical knowledge is required, it has to be taught in addition to what would be suggested automatically by a system dynamics approach. A simple example of such special knowledge is the relation between the angular velocity and the velocity of the center of a wheel rolling on a surface. Another is the addition of waves in wave optics and acoustics. No amount of theory of dynamical systems will teach us about this. Therefore, we have to be careful to state what the approach can and cannot do. We believe that we can base physics upon the CPP and that we can give students a new view—and a different and wider operational understanding—of nature, but many of the elements of instruction in physics will remain those of the well-known Standard Model.

II The Continuum Physics Paradigm

The fundamental idea of the CPP is very simple: Physical processes are seen as the result of the flow, the production, and the storage of certain physical quantities such as charge, entropy, momentum, amount of substance, and so forth.[3,25] These are the quantities which satisfy laws of balance (Section III). The processes are often maintained by differences of levels (potentials). By itself, water flows downhill, releasing energy; when it is pumped uphill, energy is used (Section V). We borrow images from the flow of water on the surface of the Earth to create abstract images of other phenomena. The structural analogy between different phenomena resulting from this view is one of the most important aspects of the CPP. It is the basis of the unification of different fields of physics,[26] and the source of the ease with which system dynamics tools can be used (Section IV and CPP II).

A. The image

If we wish to explain the world around us we have to come up with pictures or mental images. Since the world is one of continuous change, the main objective of physics must be the creation of images which help to explain how nature works as a dynamical system. These images turn out to be graphical, intuitive, and powerful: much of what we need for an understanding lies dormant within all of us—a result of everyday experience.

Everything flows… There are processes which immediately suggest the image of the flow of some "stuff"—such as in the flow of water and air at the surface of the Earth. Other substances flow as well, be they molten rocks or chemical species dissolved in the ground or in fluids. All these highly visible transport processes constitute the archetype of change and of dynamical processes as we know them. Therefore we shall take them as the source of our image of how nature works.

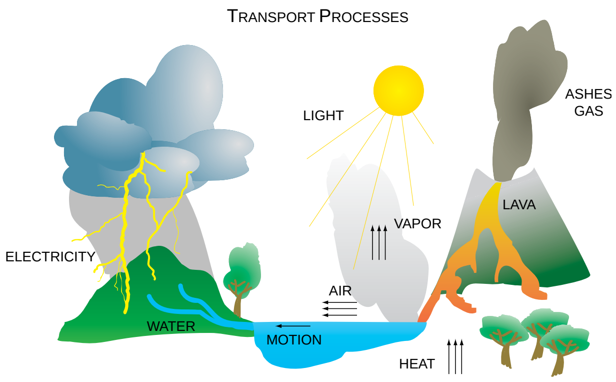


Figure 1: A world of change. The picture is a metaphor for one of the important features of nature: processes are the result of the flow of certain simple quantities.

This image can be transferred to processes involving "intangible" quantities, such as electricity and heat. Usually we accept that electrical and thermal processes may be pictured in terms of the flow of electricity and heat, respectively, and we describe the flow of heat and of electricity in analogy to the flow of water or air, just as if they were some kinds of fluids.

It is less obvious how mechanical processes could be included in this image. However, consider the following headline in a newspaper: "Storm near New Zealand causes high surf at Oahu's south shore." The simplest explanation again is in terms of a transport process. The winds down near New Zealand have quite some momentum, and they transfer part of their quantity of motion to the water. Rather than setting the water in motion (the waters near New Zealand do not travel to Hawaii), the momentum of the winds transferred to the ocean travels through the water. If it is intercepted in the right way, and surfers know how to do this, a quantity of motion can be transferred to other bodies causing them to move. All types of mechanical processes can be understood in terms of the transfer of motion through, and with, bodies.

…or is produced and destroyed… Flow processes are only a part of what is hidden behind the changes observed in nature. Just as important are those phenomena which are the result of the production or the destruction of certain quantities.

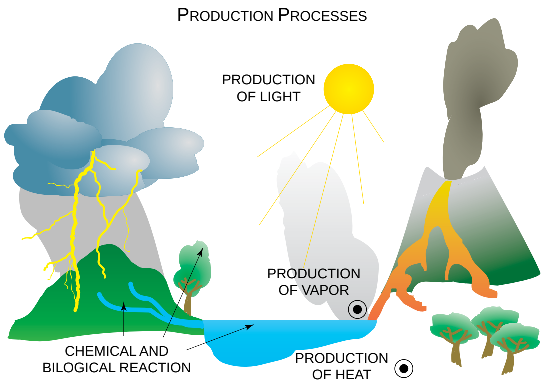


Figure 2: Processes can also be the result of the production or the destruction of certain quantities.

We discover the creation and the destruction of chemical or biological species as a major force of change. Dynamical processes can be as much the result of production and destruction of substances inside a system as they are the consequence of the delivery to, or the withdrawal from, the system of those same species. Consider an example from biology. The number of elephants living in a specific area of southern Africa in the course of time is determined as much by births and deaths as it is by migration of the animals into or out of the area. Births and deaths are for living species what are production and destruction for chemical ones. In chemical reactions, substances appear and disappear; they are produced and destroyed. Leaves of trees take up carbon dioxide and water which are destroyed in photosynthesis leading to the production of new chemical substances.

Equally, from the phenomena involving heat we know that this quantity can be produced by fire, by friction, and by a multitude of other processes. Heat appears in bodies without having been delivered to the systems. So, the amounts of chemical and biological species, and of heat can be changed inside a system without transport processes being at fault.

…and is stored. Quantities which flow or are produced and destroyed are contained inside regions of space. Elephants reside in an area of land, carbon dioxide is contained in the air, heat is inside stones. Quantities which can be stored and which are able to flow shall be called *additive* or *substancelike* since substances most visibly fit this picture.

Why do things flow? We find the answer to this question by observing what water and air do at the surface of the Earth. Simple every-day observations tell us that water flows downhill by itself, that it needs a gradient to flow. Waterfalls serve as the prototype image of how nature works.

In the case of the flow of air, heights or *levels* cannot be seen directly; therefore we have to extend the image. We know that air flows from locations of high air pressure to such locations where the pressure is lower. Therefore, we see pressure as a kind of "level." The reason for the flow is a difference of levels, and this difference is interpreted as a *driving force* for the process. This idea can be transferred to all other phenomena, including those of production and destruction.

What does energy have to do with all of this? The quantities referred to so far—substances such as air and water, quantities like electricity, heat, and momentum—are not energy. Energy is a different quantity with an altogether different role in nature. It is like the grease which makes the wheels turn, where the wheels are made of air, water, heat, electricity, and so forth.

Consider the description of water flowing uphill. We say that we have to work in order to make this happen. Energy is the measure of how much we work, or of how much a process running downhill works to drive quantities uphill. We need energy to make water flow uphill, and water falling down releases energy (Fig.3).

Next, consider an electric circuit with a bulb where electricity is made to flow with the help of a battery; electricity flows in a closed circuit. Energy, on the other hand, takes a different path: it is transported from the battery to the bulb, and from there with the light into the room. We say that the electrical current "downloads" energy in the bulb. The energy which was "downloaded" makes the bulb operate as it should, and it is transmitted to flow out of the bulb.

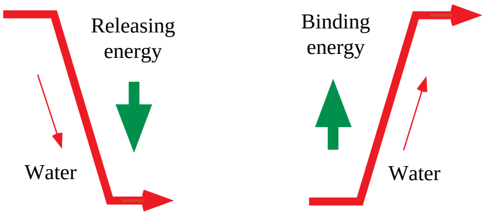


Figure 3: Water falling down releases energy which can be used in a follow-up process driving water uphill. The energy released in one process is bound in another. The vertical fat arrows symbolize the release and the binding of energy.

This example demonstrates the role of energy in chains of processes; it shows how energy is transmitted, released, bound, transmitted, and released again, and so forth. All the while, water, electricity, heat, and momentum flow (or are produced) as part of the particular processes making up the chain. This is how we can understand the dynamics of nature. For more details see Section V.

B. A unified view of physical processes

The image developed so far lends itself to a unified description of classical macroscopic phenomena. Each of the major classes of phenomena is governed by one of the additive (substancelike) quantities, accompanied by a particular potential (Table 1).

The table entries only show the tip of the iceberg. They can motivate us to search for and to develop a simple unified theory of physical processes applicable to physics instruction.

C. Formal background

In continuum physics, our knowledge of the physical world is expressed as follows. We usually identify four elements of a theory.[26] First we have to agree on which physical quantities we are going to use as the fundamental or *primitive* ones; on their basis more quantities are defined, and laws will be expressed with their help. Second, there are the fundamental *laws of balance* of the quantities which are exchanged in processes, such as momentum, charge, entropy, or amount of substance; we call these quantities *additive* or *substancelike*. 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.

Table 1: Comparison of quantities for different fields

Class of phenomena	Quantity which flows and is stored	“Level” quantity whose difference is responsible for flow
Hydraulics[a]	Volume or amount of substance	Pressure or chemical potential
Chemistry	Amount of substance	Chemical potential
Electricity	Electrical charge	Electrical potential
Heat	Heat (entropy[3])	Hotness (temperature)
Gravity	Gravitational mass	Gravitational potential
Translation	Quantity of motion (momentum)	Velocity
Rotation	Angular momentum	Angular velocity

a. It is convenient to split the phenomena having to do with substances into two groups—those dealing with transport and those having to do with chemical reactions.

Take as an example of a theory of continuum physics the simple case of the conduction of heat in rigid bodies in a single direction of space. Note that there are several alternative ways of setting up such theories; by varying the assumptions you may obtain other forms of the same theory.

As the fundamental or primitive quantities of our theory we will take heat (entropy) and temperature. To be specific, we introduce the density of entropy ρ_S, the flux density of entropy j_S, and the density of the rate of production of entropy π_S. These quantities allow us to formulate the generic law of thermodynamics, namely the law of balance of entropy which, in our case, takes the form

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial j_s}{\partial x} = \pi_s \tag{1}$$

Constitutive laws should be provided for relating the density of entropy of the body to its temperature, and the flux density to the temperature gradient. In our simple case we have

$$\begin{aligned} \dot{\rho}_s &= \rho k \dot{T} \\ j_s &= -k_s \frac{\partial T}{\partial x} \end{aligned} \tag{2}$$

Here, k denotes the specific entropy capacity of the material while k_s is its entropy conductivity. The second of these equations represents Fourier’s law. We now need additional information which is provided by the energy principle. First, we can make use of the law of balance of energy

$$\frac{\partial \rho_E}{\partial t} + \frac{\partial j_E}{\partial x} = 0 \tag{3}$$

Second, we need to know how energy and entropy are related in thermal processes. This relation is expressed in terms of the flux densities of entropy and of energy:

$$j_E = T j_s \tag{4}$$

If we combine the equations and note that the resulting relation must hold for all cases including steady-state processes we may conclude that

$$\begin{aligned} \frac{\partial \rho_E}{\partial t} &= \rho (Tk) \frac{\partial T}{\partial t} \\ \pi_s &= -\frac{1}{T} j_s \frac{\partial T}{\partial x} \end{aligned} \tag{5}$$

In other words, the relation between the energy and the temperature of the body, and the rate of production of entropy have been determined by the constitutive theory. Note that the factor $Tk = c$ is the specific temperature coefficient of energy of the material (it is normally called the “specific heat”). As mentioned before, this development by no means is the only possible one. For example, Eq.4 often is derived and not assumed.[9]

This simple example of a theory agrees with the qualitative image developed in Section II.A. There is an additive quantity responsible for the phenomenon (entropy) which may be thought of as residing in bodies, and being capable of flowing. Moreover, it can be produced (but not destroyed). Temperature serves as the thermal potential, and energy accompanies the processes; energy is transported, stored, and released or bound.

III Laws of balance: Thinking in terms of dynamics

One of the most important aspects of the unified version of physics developed on the basis of the CPP has to do with the laws of balance which are the generic laws expressing our view of the properties of the additive quantities. Our extensive experience with teaching the PS I subset demonstrates that these laws can in many ways be viewed as a guide through physics.

- They appear again and again in the same form in all fields of physics, serving as a unifying concept for the entire science.
- Models of dynamical systems can be built successfully if we begin by writing down laws of balance; in system dynamics models they indeed serve as the backbone of the entire structure from which we hang the specialized information dealing with constitutive laws (Section IV and CPP II).
- They open the door to the world of dynamics. By learning how to express them in dynamical form, students gain access to thinking in terms of dynamics rather than statics; they are empowered to formulate initial value problems without difficulty.

Therefore, teaching how to deal with laws of balance must be at the center of any approach using the CPP.

A. Accumulation and laws of balance

We believe that nature ticks as the result of the flow and the production of the substancelike quantities. In other words we believe that flow and production are the processes responsible for the change of the amounts of these quantities residing in a system as time passes.

Quantities accumulating inside systems can be counted, i.e. their amount can be specified by a number. Moreover, if we have the necessary means, we can trace the development of these numbers over the course of time. In general, we would like to be able to say how the change of a quantity comes about. This is done by accounting for the quantity. Accounting means keeping track not only of the numbers of things stored but also counting how much has come into, or how much has left, the system. And finally, accounting really means balancing the numbers, i.e. asking oneself if they add up correctly. This means asking the question of whether the amount which has crossed the boundary of a system matches the change of the stored quantity.

Obviously, there is a belief hidden behind the practice of accounting: we believe that we can tell the change of the amount of what is inside a system from knowing how much has gone into or come out of a certain area. In the same manner, if an additive quantity is not transported, we believe that we can get a handle on its change if we know how much of it has been produced or destroyed; and if the quantity both flows and is produced we still believe that we can balance the numbers. Assuming a relationship between what happens to a system content and the processes of flow and production is the basis for what we call *laws of balance*. Laws of balance simply are the mathematical tools for keeping track of additive quantities.We have to introduce formal equivalents of the terms used informally in the description given above. These are the *system content* (or rather its rate of change), *fluxes* to describe the rate of flow of the quantities, *source rates* for processes which have to do with the interaction of bodies and fields, and *production rates* (Section III.C). Our belief about how processes work lets us relate these quantities as follows: The rate of change of the system content dX/dt must be equal to the sum of all fluxes I_X, source rates Σ_X, and rates of production Π_X:

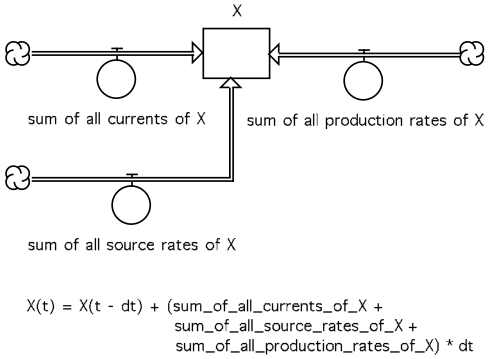
$$\frac{dX}{dt} = I_{x,net} + \Sigma_{x,net} + \Pi_{x,net} \qquad \textbf{(6)}$$

The index *net* stands for the sum of all the quantities in question.

B. Introducing laws of balance

The questions of how to set up such laws of balance and how to easily deal with them form part of the early sections of our course on introductory physics. While much of the teaching and training in this field is done without the computer and particular computing tools, it is here where system dynamics programs[13] leave their first distinct mark (see Section IV and CPP II for more details). Setting up a model of transport and production processes influencing a system is very simple if it is done with the proper graphical tools. Indeed, a law of balance is “written” simply by assembling a *stock* and one or more associated *flows* (Fig.4). Note that nature directly delivers first order differential equations rather than higher order ones. Laws of balance are first order initial value problems, while some constitutive laws deliver relations for the time derivatives of quantities. Therefore, there is no need for reducing higher order equations to sets of first order ones.

Naturally, students have to learn about the formal concepts forming part of a law of balance as well. We introduce our students to the quantities needed for formulating the laws, such as system content and its rate of change, fluxes and amount exchanged with currents, production rates and amounts produced, before setting up the relations between these quantities which constitute the laws of balance. We particularly place emphasis on the instantaneous form of the relations which is presented in the context of concrete examples with the help of images, language, and graphs long before the first equations are written. For example, the problem of the balance of number of people living in a city may be expressed by the following sentence: “The question of how fast the number of inhabitants changes is answered by the sum of the rates of birth and death, and the rates of migration into and out of the city.” We find that it takes a great deal of careful exposure to such word concepts and their graphical representation over an extended period of time for students to become conversant in dealing with the fundamental problem of dynamical systems in a generalized setting. (We revisit the concepts again and again as the physics course unfolds.) Both for didactic reasons and for letting the students get a feeling for the wide applicability of the ideas we use examples of laws of balance from every-day life and from biology and chemistry; physics appears on the stage when we start with balancing amounts of water in our initial chapter on hydraulics (see Section VII).



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X(t) = X(t - dt) + (sum_of_all_currents_of_X +
                    sum_of_all_source_rates_of_X +
                    sum_of_all_production_rates_of_X) * dt
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Figure 4: This diagram represents the graphical expression for the general law of balance formulated in Eq.6. By drawing this diagram in the program Stella,[13] the mathematical form of the law, i.e. the equation, is set up automatically. The differential equation is displayed below the graph in the form of a difference equation. (This is how it appears on the equations sheet in the program Stella.)

We use graphical methods for dealing with the mathematical problems associated with balancing physical or other quantities independently of whether or not students have had some prior exposure to calculus. We believe that its is absolutely mandatory that students develop a facility with graphical tools which must complement their ability to do symbolic and numerical manipulations with and without the computer.

C. Formal background

In general, processes occurring in space call for a spatially continuous form of the laws. Currents, for example, express how much of an additive quantity is transferred across a system boundary per unit time. The current density $\mathbf{j}_X$ is the formal expression of how the current is distributed over this surface. Therefore, the flux and the current density are related by

$$I_X = -\int_{\mathcal{A}} \mathbf{j}_X \cdot \mathbf{n} dA \tag{7}$$

Here, X may stand for volume (or mass or amount of substance) in the case of water, and for entropy and charge in the case of heat and electricity, respectively. Note that the unit normal vector $\mathbf{n}$ points away from the volume enclosed by the surface under consideration.

For some of the additive physical quantities there exists the possibility of transport into or out of the system in a manner different from what we have just explained. Entropy, momentum and angular momentum may be brought into a system without flowing across its surface. This is the case if these quantities are transported through a field and end up in, or are withdrawn from, the system directly at every point inside. While the surface-like transport introduced above is either *conductive* or *convective*, we may use the term *radiative* for the transport which is the result of the interaction of bodies and fields. Instead of current densities, we introduce volume densities of source rates σ_X to describe formally what is going on:

$$\Sigma_X = \int_{\mathcal{V}} \sigma_X dV \tag{8}$$

We introduce the volume density of rates of production π_X to describe processes of production and destruction. The integral of this quantity over volume furnishes the rate of production Π_X of quantity X in the system:

$$\Pi_X = \int_{\mathcal{V}} \pi_X dV \tag{9}$$

Finally, we have to express the system content in a similar way. The quantity X which is stored in a particular volume is calculated in terms of the density of X which we write as ρ_X. Therefore, we have

$$X = \int_{\mathcal{V}} \rho_X dV \tag{10}$$

To write down the equation of balance of X for the spatially continuous case we simply have to add the different expressions introduced in Equations (7) – (10):

$$\begin{aligned} &\frac{d}{dt}\int_{\mathcal{V}} \rho_X dV \\ &\quad = -\int_{\mathcal{A}} \mathbf{j}_X \cdot \mathbf{n} dA + \int_{\mathcal{V}} \sigma_X dV + \int_{\mathcal{V}} \pi_X dV \end{aligned} \tag{11}$$

With the help of the divergence law, this transforms into the well known partial differential equation expressing the balance of quantity X:

$$\frac{\partial \rho_X}{\partial t} + \frac{\partial j_X}{\partial x} = \sigma_X + \pi_X \tag{12}$$

written for the purely one-dimensional case. Eq.1 is a special case of this expression.

We recognize Eq.6 as the “lumped parameter” form of the laws of balance as they are written for spatially continuous cases. Therefore, the Physics of Systems I (PS I) can be viewed as the subset of continuum physics which neglects spatial variation of the properties of systems and their interactions with the surroundings. To give a couple of examples, if we use momentum for X and do not allow for convective momentum currents, we end up with the usual form of Newton’s law for closed systems (bodies); remember that momentum is conserved and therefore does not admit of production terms. Using entropy as the quantity under consideration, we end up with the most general expression of the Second Law for control volumes.[3] Here, entropy can enter a control volume due to conductive and convective transport, and as a result of absorption. Moreover, it can be produced.

IV A system dynamics modeling approach to physics instruction

System dynamics modeling is a general methodology for producing models of dynamical systems. It grew out of cybernetics and control engineering[11,12] which can be seen as children of physics and biology. It was designed specifically to help with modeling nonphysical and nontechnical systems.[27] For this purpose, a perfectly simple and graphical approach (systems thinking) was created which should help us to come to terms with the art of modeling even if we are not trained in mathematics.[13] In short, the system dynamics methodology can serve as a practical and explicit solution to the issue of modeling in physics instruction.

The general nature of system dynamics (SD) makes it applicable also to fields outside the physical sciences—such as biology, ecology, management, social sciences, and economics.[28] If we look for a methodology which has the potential of unifying a larger part of our theoretical and practical knowledge—here it is.

A. Modeling in physics

Modeling has been called the name of the game in physics. In recent years, David Hestenes and his colleagues have proposed a modeling theory of physics instruction[29] and have applied it very successfully to examples of physics instruction at universities and at high schools.[30] Their work applies the scientific method to physics instruction and provides for one of the first examples which explicitly teaches the modeling approach as part of introductory physics. Their inventory of the structure of factual knowledge gives them an understanding of how procedural knowledge should be included in instruction. For them, the structure of scientific knowledge is model based which means that a modeling strategy should be taught when we introduce students to physics (and to other sciences). Not surprisingly, in most of their examples, at least as published in the literature, they use Newtonian mechanics of mass points as the stage for outlining the approach.[29] They maintain, however, that the modeling methodology should be applicable to all areas of physics.

The research effort started by Hestenes recognizes the important role played by conceptual difficulties.[22] It is hoped that instruction which explicitly acknowledges such problems will be able to counter them effectively. It might be important to note that the teaching of model construction and model deployment is an example of a constructivist approach which, in recent years, has been of some interest in didactic research concerned with conceptual difficulties.

B. System dynamics modeling

System dynamics provides a methodology and tools for modeling and simulation of dynamical systems mostly from the social sciences and management. Since many practitioners of system dynamics are not engineers or scientists, using the full rigor of mathematical systems theory for the teaching of SD would be inappropriate. Therefore, a didactic approach has evolved which uses intuitive graphical metaphors for representing what at the core is a mathematical problem. In the language of Stella,[13] dynamical systems and processes are represented by *stocks* which model quantities which accumulate, by their associated *flows*, and by additional quantities which provide for the (feedback) relations necessary for computing the flows (Fig.5). Dynamical processes are understood as the result of the accumulation of some quantities whose flows are interrelated in a more or less complicated manner leading to a network representation of the relations governing the behavior of the system. In this approach models of dynamical systems are built on the computer screen using graphical tools before equations are introduced for representing particular relations.

In mathematical terms, stocks and flows together represent first order differential equations (initial value problems) involving the accumulating quantities (Fig.4). Specifying the initial value of a stock and the proper relations for the flows fully defines the differential equation. Therefore, what is commonly thought of as being the most demanding step in modeling of a dynamical system, namely the setting up of differential equations, in the system dynamics approach turns out to be rather simple. A system dynamics diagram as in Fig.5 clearly visualizes the important distinction between laws of balance (the stocks and flows) and the associated constitutive laws specifying the flows; remember that this distinction is a crucial part of the structure of continuum physics.

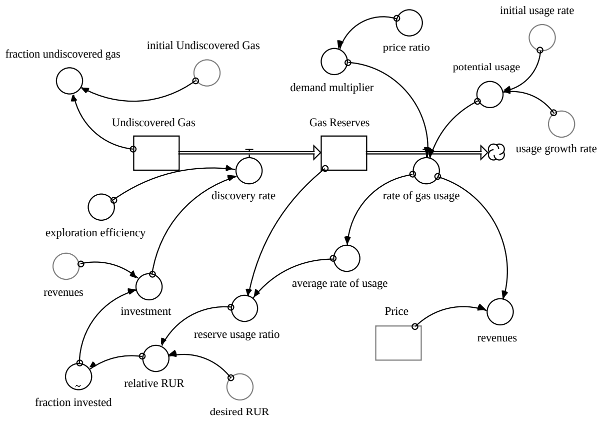

Figure 5: A part of a System Dynamics model of the natural gas usage in the United States[31] written in Stella. Notice the different graphical elements which represent different parts of the structure of of a dynamical system. The rectangles represent stocks, while the fat arrows denote flows. The circles are additional variables used in creating the (feedback) relations expressing the flows in this structure. The combination of GasReserves and its associated flows represents a law of balance, the other relation are c onstitutive relations.

For several years now, advocates of the system dynamics methodology have stressed the importance of this approach for new forms of learning.[32] Groups of teachers—with the active support of the NSF—are developing courses and materials for teachers for K-12 education.[33] Physics, however, has been conspicuously absent from this development. There are examples from physics included in books on general system dynamics modeling,[28] but commonly they do not do any justice to either physics or system dynamics. The general feature of all of these attempts is the complete absence of a systems view of physical processes, which commonly leads to an abuse of system dynamics tools for the numerical solution of previously derived differential equations. So far, we know of only one research project where the attempt is made to use Stella[13] as an actual modeling tool in physics;[34] it is based on the Standard Model of physics instruction, and the applications are restricted almost exclusively to mechanics.

C. System dynamics modeling in CPP physics courses

You probably note both the similarity and the differences between our presentation of the structure of physical theories in continuum physics and the structure of physics as outlined by Hestenes.[29] As we see it, SD modeling adds an important methodological dimension to the modeling approach advocated by Hestenes and his colleagues (CPP II). We believe that continuum physics leads to a clarification and a generalization of the foundations of physics and therefore is of particular interest if we wish to extend the modeling strategy to all fields of physics. As we have already seen, the basic ideas which are at the core of continuum physics can be put in rather simple and graphical language. The mathematical aspects of continuum physics, however, are much too complicated for direct adoption in an introductory physics course. System dynamics modeling can overcome this chief obstacle to successfully use the CPP in physics instruction.

Nature and physics provide examples of well known additive quantities—those which appear as stocks in an SD model diagram. The flows are used to represent the three different terms on the right-hand side of Eq.6. Moreover, the distinction between laws of balance and constitutive laws known from continuum physics carries over to system dynamics modeling. Therefore, our approach to modeling the physical world can be expressed as follows:

1. Look for the proper quantities for which laws of balance should apply (Table 1).
2. Write the laws of balance in graphical form to create the backbone of stocks and flows of the model as in Fig.5.
3. Now you can embark on the—usually much more complex—task of finding the flows (the constitutive laws).

This simple procedure can guide us through much of physics. It reflects the CPP at the simple level of homogeneous systems, unites different subjects in introductory physics by making use of analogies, and—together with the proper tools—can lead to increased student centered learning of physics (CPP II). Our experience with system dynamics modeling stretches all the way from applications in introductory college physics, to serious engineering models,[35] and to examples dealing with technology and society.[36] Weaving the CPP and system dynamics modeling into a single fabric has opened up entirely new avenues for education in the sciences and engineering,[37] and it unites physics with fields which commonly are looked at as being altogether different.

V Energy in physical processes

The books on continuum physics do not offer a simple interpretation of the role of energy in physical processes, and standard physics instruction treats the subject differently in every field making it virtually impossible for a unified image of a single physical quantity accompanying all physical processes to grow.[38] Therefore, we have to construct new ways of including the energy concept in courses which use the CPP approach.

A. The balance of energy

In its purest form in classical physics—before we introduce different constitutive laws into the equation of balance of energy—the energy concept appears as follows: There is a quantity called energy which can be transported into and out of systems, and which can be stored in systems. Since it is also a conserved quantity, it satisfies the following equation of balance:

$$\dot{E} = I_{E,net} + \Sigma_{E,net} \tag{13}$$

The symbol E stands for the energy content of the system, while I_E denotes an *energy current*; Σ_E represents a source rate of energy associated with the interaction of bodies and fields. Note that there is no talk of different “forms” of energy, nor of “conversion” or the like. So far, all we can say is that there is a single new quantity which can flow into and out of systems.

The flow of energy is accompanied by the flow of one or more of the additive quantities of physics. For example, water under pressure delivers energy at a rate

$$I_E = P I_V \tag{14}$$

(P is the pressure, and I_V stands for volume flux) while in conduction of heat, energy and entropy are related by

$$I_E = T I_s \tag{15}$$

at the system boundary. These observations allow for a unified interpretation of the transport of energy in conductive transport phenomena: energy flows at the same time as additive quantities are transported across system boundaries (Fig.6). The factor relating the two flows is the proper potential. This has led to the interpretation of the additive quantities as *carriers of energy,* and the potential as the associated *load factor.*[20] Different “forms of energy” are distinguished by the additive quantities accompanying the transport phenomena. Therefore, there is no need for different words for different instances of energy flow. There still is just a single quantity called energy which accompanies all types of physical processes.

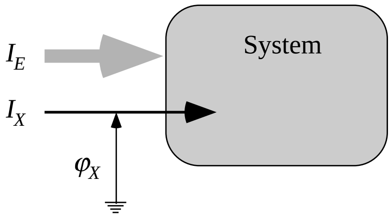

Figure 6: When an additive quantity flows conductively across a system boundary, it is accompanied by a flux of energy which is calculated in terms of the product of the flux of the additive quantity and its associated potential.

A large number of physical processes also admit of a simple image for the storage of energy together with an additive quantity. Take for example a container with straight walls storing some water (Fig.8). The amount of water in the system is equal to the product of the cross section of the container and the level of water in the tank. The energy stored as a consequence of the storage of water is easily seen to be equal to the product of the amount of water and half the level of the fluid. This image can be applied to other fields and more complicated situations such as a body with a variable entropy capacity. The graphical interpretation has been called the *fluid image* of physical processes.[39]

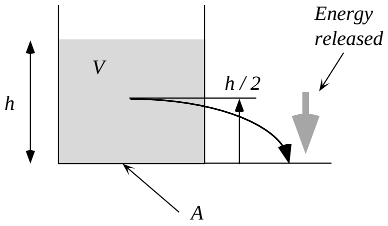

Figure 7: The amount of energy stored as a consequence of the storage of the fluid can be visualized in this picture. Discharging the water in the container to a constant level at $h = 0$ releases an amount of energy equal to how much was stored.

B. Releasing and binding energy

In the physics of systems we deal with the lumped parameter representation of systems and processes. This model requires an additional interpretation of the role of energy. If an additive quantity flows from points of high to points of low potential inside a system, energy is released (Fig.3). In the reverse process, energy is bound (used). We introduce the rates at which energy is released or bound; these rates will be called the *power* of a process. The power is calculated according to

$$\mathcal{P} = -\Delta\varphi_X \left| I_X \right| \qquad (16)$$

Note that these quantities do not appear in the equation of balance of energy (Eq.13). They have to be added to the interpretation of physical processes in the lumped parameter version (Fig.8). In spatially continuous processes, they appear quite naturally when transforming the law of balance of energy with the help of relations such as those in Equations (14) and (15). In the image created here, the concept of releasing and binding of energy replaces the notion of “energy transformation” from one form into another.

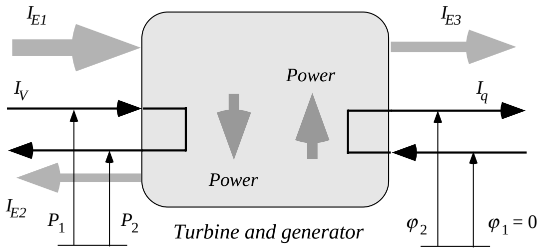

Figure 8: Flow and level diagram of an ideal turbine with generator. Energy is supplied to and withdrawn from the system together with water, and it flows out of the system as part of the electrical process. In the system, energy is released as a consequence of the fall of water from high to low pressure. In the ideal system, energy is bound at the same rate as the result of the electric process alone.

The role of energy in the CPP can be summarized as follows:

1. A single fundamental quantity accompanies all physical processes—energy;
2. it can be transferred into and out of systems, it can be stored, and it can be released and bound;
3. it is conserved;
4. in conductive transport, its current is directly related to the accompanying flow of an additive quantity (“carrier”) and the associated potential;
5. if energy is released, the power is determined by the current of the “carrier” and the difference of potentials.

VI CPP, conceptual difficulties, and phenomenological primitives

No model of physics instruction will completely agree with our everyday concepts of processes. Therefore, we will most certainly have to deal with so-called misconception in one way or another. Rather than going into the details of what these might be and how we could handle them, we would only like to bring to your attention a point made a few years ago.[16]

If we teach physics from a different perspective, the role of everyday concepts will necessarily change. What constitutes a misconception in one framework may be a very useful notion in another. Nowhere is this felt more clearly and painfully than in the science of heat. Our concepts formed outside of formal instruction lead to the idea of a quantity of *heat* which conforms closely to what used to be called *caloric* some 200 years ago. Now, in the traditional presentation of physics this constitutes a misconception. However, if we were to base the development of thermodynamics on the unsophisticated concept of heat formed in everyday life, we could arrive at the most general expression of the Second Law of thermodynamics—the law of balance of entropy—almost effortlessly[3,40] (CPP III).

Consider the following story reported by Wagenschein.[41] He observed a little girl sitting on a park bench in the sun. She placed her hand on the hot bench and withdrew it suddenly, looking at it in amazement. Wagenschein goes on to speculate how the concept of a quantity of heat must form in this child’s mind, a notion of a quantity of heat possessed by bodies and flowing into and out of them. Here we have—if we can believe the observer—a child which is forming strong and valid ideas about the world of heat. In terms of physics we would say this may serve as the source of the concept of the extensive thermal quantity. However, Wagenschein admits somewhat later that this concept will have to be abandoned in formal education—since it obviously constitutes what we today call a misconception.

This story clearly demonstrates the changing roles of misconceptions and phenomenological primitives. If we want to take children’s views of nature serious and employ them as sources for constructing an understanding of physical processes, we may have to reconsider our practice of teaching of physics.

VII A brief outline of the PS I course

A physics course based on the CPP makes extensive use of analogies. This makes it possible to arrange the subject matter in many different ways. However, some arrangements emerge fairly naturally. For example, the physics of spatially homogeneous dynamical systems (PS I; first year physics, Tables 2 and 3) certainly will precede the physics of extended systems (bodies, fields, waves; second year). In this section, a possible structure of the PS I course is outlined, and some details are discussed.

Table 2: Overview of sections of a PS I course

Title	Weeks[a]
Introduction to physics and modeling (CPP II)	2
Introduction to dynamical systems (Table 3)	10
The dynamics of heat (CPP III)	8
Transfer of momentum and angular momentum	11
The transport of fluids	3

a. At TWI, one semester comprises 17 weeks of classes.

A. Overview

One of the most distinctive features of the approach based on the CPP is this: The different fields of physics are all treated equally—they are on the same footing. There is no special group of phenomena which rules all others. In particular, mechanics does not serve as the role model of physical processes. Phenomena are not explained in terms of mechanics, i.e., they are not described as the result of the motion of (little) particles.

Table 3: Overview of first section of the PS I course

Introduction to dynamical systems	Weeks
The Flow and the Storage of Fluids	2
The Transport of Electricity	1
Inductive Phenomena and Oscillations	2
Energy in Hydraulics and Electricity	2
Rotation, Angular Momentum, and Energy	1
Laws of Balance	1
Modeling Dynamical Processes	1

On the other hand, the image of the flow, the production, and the storage of additive quantities is most easily formed and appreciated in the framework of what we might call hydraulics—a simple version of the science of the flow of water and other fluids. Therefore, we commonly start a physics course with an exposition of ideas derived from fluid flow and storage. This allows us to introduce laws of balance, and the concept of differences of “levels” as the driving force for flows. Simple hydraulic systems can be described in terms of capacitance, resistance, and inductance, setting the stage for the discussion of electrical phenomena.

Having access to two fields covering different phenomena already allows us to make use of analogies. Volume (as a measure of an amount of a fluid) and electric charge both admit of currents, and both satisfy a law of balance. Energy may be introduced as the quantity relating hydraulic and electric processes, and simple system properties such as capacitance, resistance, and inductance may be seen to exist in both fields (Table 4). If we add maybe one more class of phenomena—such as rotation of rigid bodies about a fixed axis—we already have a rich and diverse playing ground for most of the concepts and methods needed to deal with dynamical systems and appropriate modeling strategies (Table 3).

These subjects conclude the introduction to dynamical systems. We may then proceed with an exposition of thermal phenomena, followed by chemical change. In the PS I course, mechanics can be dealt with much later than in the Standard Model of physics instruction. Building on the knowledge gained about additive quantities, laws of balance, the role of energy, and systems properties (Section B.), mechanical processes can be introduced in much the same way as the previous fields. We find that mechanics tremendously benefits from a systems view of physical processes.

The PS I subset can be concluded with a brief outline of flow processes in open systems. Here we introduce the concept of convective currents, and we open up a rich field of applications in engineering.

B. PS I, simple linear systems, and analogies

The simplest dynamical systems found in the different fields of physics are made up of strongly similar elements (Table 1). In control systems engineering,[12] we speak of linear systems having the properties of capacitance, resistance, and inductance. On the basis of these elements, the analogy between different fields can be made particularly plain. There exists a strong positive feedback between the use of analogies and graphically oriented system dynamics modeling.

VIII Summary and outlook

We have presented an overview of a new approach to the teaching of introductory college physics which builds on the Continuum Physics paradigm and makes use of an explicit (system dynamics) modeling strategy. In this paper we have discussed the motivation for replacing elements of the Standard Model of the introductory college course. The following two papers will present details concerning the modeling strategy (CPP II) and a novel way of including a theory of thermal phenomena based on the dynamical aspects of heat (CPP III).

The paradigm has been applied mostly to the first year physics course which deals with spatially homogenous systems (PS I). We are currently working on extending the approach to spatially continuous systems (bodies, fields, waves), and we are investigating the possibility of increasing the use of system dynamics modeling labs—combined with standard experimental labs—to strengthen learner-centered learning strategies.

Table 4: Simple system properties

Class of phenomena	Capacitors	Resistors	Inductors
Hydraulics[a]	Pressure vessels	Fluids and pipes	Fluids and pipes have hydraulic inductance
Electricity	Electric capacitors	Resistors have resistance	Inductors have inductance
Heat	Bodies have entropy capacity	Entropy transfer resistance	??[b]
Gravity	Water containers and artificial lakes	Not commonly used	Not commonly used
Translation	Inertial mass is the momentum capacitance	Friction leads to resistance	Springs have inductance
Rotation	Moment of inertia is the angular momentum capacitance	Friction leads to resistance	Rods have inductance

a. Only bulk flow of fluids. The subject can be extended to include diffusion, and chemical change.

b. Thermal inductance exists at very low temperatures and leads, among others, to the phenomenon of second sound. Having a table like this with one or several blank spots has induced many of our students to actively search for analogies as a way to understand nature.

As to the issue of quantum physics, we would like to call upon the community of educators in physics to investigate in depth if the concepts created in the CPP could serve as a gateway to and a strong foundation for the world of quanta.

We find that—apart from the enthusiasm generated in students for a learning strategy which they see as opening up interesting new and relevant knowledge and methods—a physics course based on the CPP addresses several of the issues discussed in didactics in recent years. Moreover, it opens physics to the larger world of general sciences and social studies. An education which makes increased use of (system dynamics) modeling is worth investigating more closely.

Acknowledgments

I would like to thank my friends Werner Maurer and Martin Simon without whom this project could not have been carried through. Werner Maurer and I created the CPP approach from important developments in physics, modeling, and didactics, which took place during the last 30 years or so. Werner's intellectual honesty and relentless criticism of our work has often served as the driving force for new ideas and developments. Martin Simon and I have been using modeling in solar energy engineering courses and thesis work in engineering departments, and lately we have been teaching a graduate course in system dynamics which brings together people from the sciences, social sciences, and business. Martin's interest in applying system dynamics to non-technical fields has been particularly stimulating for our desire to integrate physics with the wider world of learning.

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[17] Looking at students’ concepts as the source of powerful and useful phenomenological primitives—rather than misconceptions—opens avenues for dealing with these concepts in a positive way: they may become the source of constructive development in the learning of a science. (The term “phenomenological primitive” was coined by A. diSessa, Reference 18). For examples of how physics teaching might be changed to take account of phenomenological primitives, see H.U. Fuchs, “Entropy in the teaching of introductory thermodynamics,” Am. J. Phys. **55**,215-219 (1987), and H.U. Fuchs, “Do we feel forces?” In J.D. Novak ed., Reference 15, Vol.III, p. 152-159. For a recent overview of the issues of misconceptions and phenomenological primitives see D. Hammer: “More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for educations research,” Am. J. Phys. **64**,1316-1325 (1996).

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[37] M. Simon and H.U. Fuchs, “System Dynamics in engineering education,” *Proceedings of the 1995 International System Dynamics Conference* (Tokyo, 1995).

[38] Physics still carries the burden of the historical development of the energy concept. The myriad names used for energy under different circumstances are witness to a bewildering view of what energy might all be about.

[39] W. Maurer, “Der Impuls im Flüssigkeitsbild,” Praxis der Naturwissenschaften: Physik **45** (4),35–40 (1996).

[40] See *The Dynamics of Heat* (Reference 3), Chapter 1. In the Interlude it is demonstrated how classical thermodynamics as a theory of the dynamics of heat can be based on the caloric theory of heat.

[41] M. Wagenschein, *Ursprüngliches Verstehen und exaktes Denken* (Klett Verlag, Stuttgart, 1970), pp. 101–102 and 108. In the didactics of physics Wagenschein was one of the original and creative thinkers who—apparently long before others—brought up the issues of phenomenological primitives, misconceptions, and the sources and the genesis of understanding.