A Systems View of Natural Processes: Teaching Physics the System Dynamics Way

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ABSTRACT: There exists a view of how nature operates—originating in classical continuum physics—which conforms completely to the core concepts of system dynamics. Simply stated, in the Continuum Physics Paradigm, physical processes are pictured as the result of the flow, the production, and the storage of some fundamental and easily visualized quantities—such as fluids, electricity, heat, and motion. If we base our teaching of physics on this paradigm, content matter (physics) and methodology (system dynamics modeling) form an organic unit. Unlike with the conventional mechanistic view of physical processes—where system dynamics must remain a method artificially superimposed on a non-systemic science—physics will itself have a systemic structure, and in return will help foster systems thinking in other fields. Moreover, the Continuum Physics Paradigm can be used for physics instruction at virtually any level of students' maturity or formal sophistication, ranging from primary school to graduate school. Last but not least, physics joins humankind's endeavor of making sense of the natural, technical, and social world on the basis of a unified image.

Images of change

Look at the natural world out there. How does it operate? What makes this great dynamic engine called the universe, including our beautiful planet, tick? Answering these questions will lead us right to a systems structure of physical sciences.

Everything flows… The most directly accessible and visible processes on our planet are those of the flow of water and air. Together, these phenomena create a good deal of what we see happening around us. The atmosphere, and the oceans and rivers present us with the unique opportunity to witness how nature operates at the deepest level. Water and air flow to create some of the most important and beautiful phenomena. Indeed, we say that the phenomena are the result of this flow (Fig.1).

Other quantities flow as well, adding to our list other important classes of phenomena. Heat flows from the depth of the Earth, or with the help of fluids from point to point at the surface of our planet, or from the Sun out into the solar system. Electricity flows as well, giving rise to electric (and magnetic) processes. Technical appliances add much to our experience with electrical phenomena, and we explain the processes again in terms of the flow of electricity.

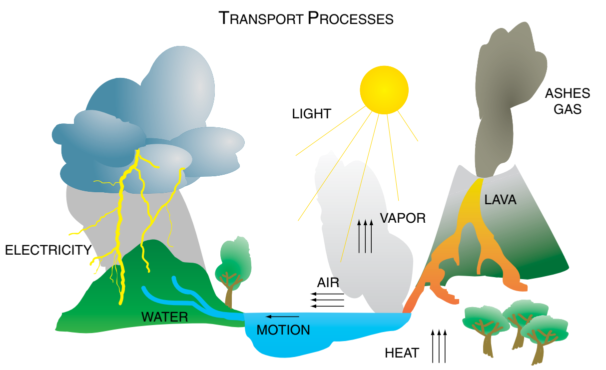

Figure 1: A large part of the phenomena we know from everyday life can be explained in terms of the result of flow processes. We transfer what we observe in the case of water and air to those fields which are beyond our direct sensory experience, such as the flow of heat or electricity.

These last two examples are important in that they prepare us to talk about the flow of invisible quantities as if they were water and air. The importance of this point cannot be overstated. First, we learn how to deal with "stuff" we do not see, we learn how to create images for processes which are governed by "imponderable" quantities. Second, it is the source of a unified description of natural processes. How should we ever arrive at a unified view of natural, technical, and social processes if one of the great old subjects presents itself as a flee market of phenomena and concepts—where thermodynamics, mechanics, electricity and magnetism, and fluid dynamics each form a separate world?

Let us take the unifying view serious and extend it to the motion of bodies. Consider how a storm near New Zealand can produce high surf at Oahu's south shore—as reported in my favorite headline of one of Hawaii's newspapers in the Summer of '95. The winds down under have momentum, or, as Newton might have said, they have an amount of motion. By blowing over the ocean, they impart part of their motion to the water. Now, the water is not set in motion, it does not flow to Hawaii. Rather, momentum is transported through the water all the way to distant shores where it can be picked up by experienced—and not so experienced—surfers. Note, motion travels *through* bodies, just as heat and electricity do.

…or is produced and destroyed… Flow processes are only a part of what is hidden behind the changes observed in nature. The other great source of change are the processes of production or destruction of some of the same quantities which can flow (Fig.2).

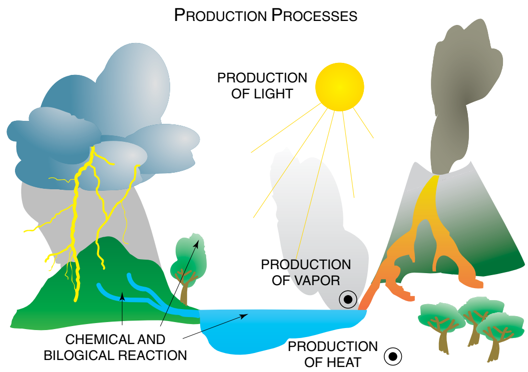

Figure 2: Processes may also be the result of production or destruction of some of the physical quantities. In particular, amount of substance and heat are not conserved, and their production and destruction has to be considered in physical processes.

Substances such as water and air, CO_2 and minerals, and the objects made out of them, are subject to chemical change—they undergo chemical reactions. Some of the substances disappear, and new ones arise. We even can add light to the list of "substances" which can be created and destroyed.

There is one more centrally important case of production: heat is produced in the multitude of irreversible processes we know—fire, friction, radioactive decay, the absorption and emission of light, and the flow of electricity, substances, and heat itself. Since heat cannot be destroyed, the amount of this quantity can only increase.

…or is stored. The same quantities we imagine flowing through space, or being created and destroyed, must occupy space. They are contained in bodies or regions of space out of which, and into which, they are flowing. In other words, they can be stored. Storage, flow, and production together are the source of change in nature.

Driving forces for change. Why do processes of change occur? Again we can derive a simple image from the case of water and air. By itself, water flows downhill. We need a difference of levels for this to happen. Air flows from points where the pressure is high to those where it is lower. Pressure therefore serves as the level quantity associated with the flow of substances. [Note, that the word "level" denotes a quantity altogether different from what in many system dynamics circles is called a level. The levels whose differences serve as driving forces are not the same as accumulating quantities for which we would introduce stocks.]

Each class of phenomena has its own level and driving force: pressure for fluid flow, electrical potential for electricity, temperature for heat, speed for motion, and the chemical potential for chemical change.

Energy. Energy is associated with all the processes mentioned. It accompanies all of them, which means that it is not specific to any of them. There is only one quantity called energy—not the myriad "types of energy" known from classical physics instruction.

Energy is *released* when one of the accumulating quantities (fluids, electricity, heat, motion) flows from a higher to a lower level (thin horizontal arrows labeled I—for current—in Fig.3), and it is bound if the quantities are "pumped uphill." The fat vertical arrows in Fig.3 labeled $\mathcal{P}$—for power—denote the rate at which energy is released or bound. Energy can be *transferred* from system to system (fat horizontal arrows labeled I_E in Fig.3), and it can be stored in systems. Moreover, it cannot be produced or destroyed. These are all the properties of energy needed to explain what is happening in nature. Energy is not used, nor is it generated, nor is it transformed.

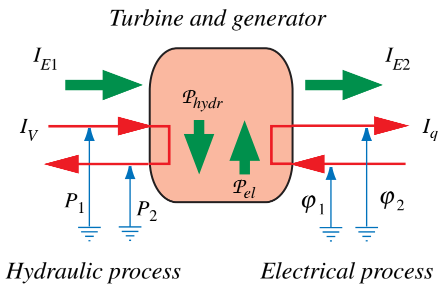

Figure 3: Energy can flow into or out of systems (I_E). It can be released or bound ($\mathcal{P}$) if fluids, electricity, heat, or motion flow either "downhill" or "uphill." And it can be stored in systems. The thin vertical arrows denote levels or potentials.

Note that none of the quantities introduced to explain physical processes—fluids, electricity, heat, motion—is energy. Energy is altogether different. When the fundamental quantities flow, or are produced or destroyed, energy accompanies the process.

An Example: The flow, the creation, and the storage of heat

Fluids, electricity, heat, and motion are introduced to account for what happens in dynamical processes in nature. Their flow, production, and storage are held responsible for the processes. Witness how easy it is to create the image of the role of these quantities.

Take the case of heat. We have very valuable everyday knowledge of the properties of heat. Heat is responsible for making stones warm, or for letting ice melt, and it is contained in these same bodies. It flows into and out of them. It can be created, but it cannot be destroyed. Indeed, we need this latter property to account for the irreversibility in physical phenomena. Moreover, when flowing from points of high temperature to points of lower temperature, energy is released which may be used to drive a heat engine. This is Carnot's image of how heat engines work.

Now combine the fundamental properties—heat can flow, it can be produced, and it can be stored—into a law of physics: laws of balance tell us that the sum of all currents of heat and of the rate of production of heat determines how fast the amount of heat in a body is changing. Put this statement into the form of a system dynamics diagram, i.e. the appropriate structure of a stock and some flows (Fig.4), or turn it into an equation. What you have just obtained is the most general form of the second law of thermodynamics—the law of balance of entropy.

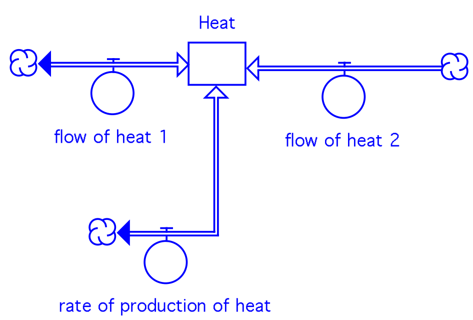

Figure 4: The system dynamics representation of the law of balance of entropy—the most general form of the second law of thermodynamics—ready for use in the computation of dynamical thermal processes. Note that transfers (currents) and rates of production are denoted by the same symbol (flows).

The quantity I have called heat is entropy. No fussing about a “strange” and “wonderful” quantity “ingeniously invented” by a “most beautiful physical theory”—thermodynamics. On the basis of physical systems thinking, and supported by system dynamics tools, kids can create this image which is the starting point for an investigation of dynamical thermal processes—reversible and irreversible. If you wish to know more about this story, have a look at my book, *The Dynamics of Heat* (Springer, 1996).

A unified view of natural processes

Since all phenomena are explained as resulting from the flow, the production and the storage of certain quantities, we can expect strong similarities between different fields of physics. The source of the structural analogies can be found in the existence of what may be called a “substancelike” quantity and an associated level for every fundamental type of physical process (Table 1).

The table entries can motivate us to search for and to develop a simple unified theory of physical processes applicable to physics instruction. For example, we find that in each field there exist elements having analogous functions (see Table 2). Obviously, system dynamics structures of such systems must all look essentially the same.

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	Volume or amount of substance	Pressure or chemical potential
Chemistry	Amount of substance	Chemical potential
Electricity	Electrical charge	Electrical potential
Heat	Heat (entropy)	Hotness (temperature)
Gravity	Gravitational mass	Gravitational potential
Translation	Quantity of motion (momentum)	Velocity
Rotation	Angular momentum	Angular velocity

System dynamics modeling in physics

You all know system dynamics, so I can be brief with my remarks about how to apply system dynamics modeling within the structure of physics which I have created here. Obviously, we start with thinking about how nature works by formulating the laws of balance of the appropriate quantities which flow, are produced, and are stored. The laws of balance are represented by structures of stocks and flows. Hardly anywhere else do we get such a clear image of the importance and the meaning of stocks and flows as we do in physics—if we are prepared to look at nature through the eyes of a “continuum physicist.”

Once we have the stocks and flows, i.e., the laws of balance, we have to determine the flows. Physicists and mathematicians speak of the need for formulating special laws, material laws, or constitutive relations. Children equipped with Stella know intuitively that that’s what is required. We ask which other important quantities the flows and the rates of production depend upon, and we slowly create the structure of (feedback) relations resulting in a finished model of a physical process.

Table 2: Simple system properties

Class of phenomena	Capacitors	Resistors	Inductors
Hydraulics	Containers and pressure vessels have hydraulic capacitance	Fluids and pipes are systems with hydraulic resistance	Fluid in pipes have hydraulic inductance
Electricity	Electric capacitors have capacitance	Resistors have resistance	Inductors have inductance
Heat	Entropy capacity	Entropy transfer resistance	
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

Systems and process thinking in physics

Can physics enhance systems thinking? Obviously, it can only do so if it is a systems science itself. If it is presented as such it can indeed increase our understanding of system dynamics structures and of the process of modeling according to the system dynamics methodology.

In physical systems thinking, feedback loops arise naturally as a result of the modeling process. We may start our thinking by first asking about the existence of such loops, but the practice of modeling in physics suggests that there are large areas of applications where thinking in terms of the flow, the production, and the storage of the fundamental quantities should precede these questions. In other words, *thinking about processes* complements systems thinking.

Also, the phenomenon of induction and the geometrical relations known from kinematics teach us that there are special laws which specify the time rate of change of a physical quantity rather than the quantity itself. To get the quantity, we have to integrate its rate of change. This mathematical operation is not a law of balance—and therefore should not be represented by structures of stocks and flows. Although there is no difference between a law of balance and the process of integrating a rate of change on a purely mathematical level—the resulting equations have the same structure— there is a fundamental difference between these two classes of laws which we should never forget. Physics points out this fact, and a dose of physical systems and process thinking may even help us in streamlining our thinking when it comes to applications in non-physical and non-technical fields. Finally, this suggests that creators of system dynamics tools may wish to think about making a distinction between structures of *stocks and flows*, and simple integrators of rates of change, i.e. structures of "*states and rates*." [Note that I do not use the term "levels and rates", since levels are different quantities in physics.]

System dynamics in physics and beyond

At Technikum Winterthur, Werner Maurer and I have been designing introductory college physics courses based on the Continuum Physics Paradigm for the last 15 years. In 1987 we discovered Stella and the system dynamics methodology and realized that we had been working on a system dynamics structure of physics all along. Step by step we integrated system dynamics modeling in our courses, and we now use it in a combined modeling and experimental lab—an integrated learning environment—to accompany the basic course on the physics of dynamical systems (the first of two years of physics instruction in the engineering departments of our school). In addition, system dynamics diagrams are used frequently in discussions of physical processes in lectures and recitation.

We have been involved in teaching college preparatory physics courses, and we have trained upper secondary school teachers who teach prospective engineering students. The enthusiasm with which they have applied system dynamics modeling in the integrated learning environments has been positively refreshing. Currently we are working on a textbook for high school physics which makes use of the approach described here.

Shortly after Werner Maurer and I started on our project, Martin Simon joined us, and he and I have been busy designing solar energy courses which make heavy use of modeling of dynamical systems. Students trained in the physics of dynamical systems take very easily to a methodology which is becoming more and more important in engineering work, and they have been using Stella and other modeling software in novel ways in their diploma thesis work.

Lately, we have been able to build up a graduate course on general system dynamics modeling bringing together students from different fields—so far mostly from engineering, the sciences, business and management. Martin Simon is particularly interested in applying what we have learned to business process modeling. In short, our early involvement with a form of systems physics is beginning to pay off in many other fields as well.

Background material

An in-depth study of the dynamical structure of thermal processes, including a discussion of the unified view of physical processes described here, can be found in H.U. Fuchs, *The Dynamics of Heat* (Springer-Verlag, New York, 1996). Recently, I have finished three reports which detail the approach developed by Werner Maurer and myself (The Continuum Physics Paradigm I–III, Technikum Winterthur, Winterthur, Switzerland).

System dynamics tools have been used for modeling dynamical physical processes before. Unfortunately, most examples do not do much justice to physics or system dynamics (B. Hannon and M. Ruth, *Dynamic Modeling*, Springer-Verlag, New York, 1994, Chapter 30). Much too often, it is declared that physics is "different" in that the differential equations governing the processes are already known, and we therefore can (ab)use system dynamics tools to simply solve these equations. However, lately, some serious attempts have been made to include system dynamics modeling in physics instruction and thus rejuvenate the learning and teaching of this science (H.P. Schecker, Modeling physics: System Dynamics in physics education, The Creative Learning Exchange **5**(2),1–8, Spring 1996; H.P. Schecker, *Physik – Modellieren*, Ernst Klett Verlag, Stuttgart, 1998; CC-STADUS Project, http://www.teleport.com/~sguthrie/cc-stadus.html). Still, to my knowledge, the projects do not make use of a general systems view of physical processes, and thus forgo much of the power of system dynamics in physics education.