The Continuum Physics Paradigm in physics instruction
II. System dynamics modeling of physical processes

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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 second paper in a series of three describes the system dynamics methodology of modeling physical processes, introduces basic elements of physical dynamical models, and presents important examples of modeling in various fields of physics. An approach which can make an integrated experimental and modeling lab the center of the learning of physics is outlined, and we discuss experience with teaching our courses to engineering and other non-science students.

I Introduction

This paper describes in some detail how system dynamics modeling can be integrated with the Continuum Physics Paradigm (CPP) and with lab based activities.

The Continuum Physics Paradigm, which serves as the basis of a revised course on introductory college physics, was outlined in the first paper in this series (CPP I).[1] In simple terms, the CPP takes as its starting point the observation that physical processes are the result of the flow, possibly the creation, and the storage of some easily visualized fundamental quantities such as momentum, entropy, charge, amount of substance, and so forth.[2],[3]

This view of nature can be transformed into models as they are known in physics in a sequence of simple, yet powerful steps. Rather than standing at the beginning, the formal representation of processes in terms of mathematical equation comes at the end of this sequence. Intermediate between image and equations is what we call system dynamics modeling.

System dynamics may be looked upon as a particular way of dealing with dynamical systems. The world of dynamical systems knows many forms of modeling, among them the work of mathematicians accompanying developments in dynamical systems; control systems modeling and finite element modeling in engineering; or the practice of computational physics in physics research. Common to all these activities is their strong reliance upon formal mathematical procedures. Also, in many cases, advanced programming techniques are used.

Among the ways of dealing with dynamical systems, system dynamics[4] stands out because of its simplicity and generality. It uses a simple metaphor and has spawned the creation of user friendly modeling and simulation tools.[5] It is general in the sense that the metaphor may be applied to many different fields where dynamical processes are of interest.[6]

System dynamics is a child of cybernetics and control engineering. Created toward the end of the 1950s, it was first applied to studies of industrial and urban dynamics.[4] Today, it is mostly used in business environments,[7] in social sciences, and by ecologists. The practitioners in these fields often have in common that they are not exposed to the kind of training in mathematics physicists or engineers normally are subjected to.

They basic metaphor used by system dynamics to map the world of dynamical systems onto models are the stock and the flow.[8] Stocks represent quantities which are imagined as accumulating in systems, and flows represent ways of changing the amount of the accumulating quantities. It does not take much phantasy to see the strong similarity between this metaphor and the CPP. System dynamics perfectly fits the basic image developed in the CPP, and the tools developed for system dynamics are so simple and user friendly that they make modeling accessible to students at an early stage in their education. Modeling of dynamical systems performed by students in introductory physics becomes a reality.

We wish to emphasize that we believe that system dynamics modeling and the application of the Continuum Physics Paradigm should go hand in hand in physics teaching. We believe that leaving out either one of the elements destroys the possibility of the synergy between content (CPP) and form (SD modeling) in a physics course. Stressing modeling more strongly in physics instruction has been advocated before—with[9] and without[10] the use of SD tools. However, we think that modeling on the basis of the Standard Model of physics instruction will not lead to the desired result. On the other hand, just trying to implement some of the important aspects the CPP in introductory physics without the proper supporting measures may be too difficult for our students. System dynamics modeling makes it possible to deal with the dynamical problems which are an integral and interesting part of classical (continuum) physics.

The present paper (CPP II) is organized as follows. In Section II we briefly discuss the structure of theories of continuum physics. This will prepare the ground for us to see how system dynamics modeling fits this structure. Section III introduces SD modeling in physics. First we discuss the role of our fundamental image of nature in the choice of a modeling methodology. Then we present a simple example to demonstrate how SD models are constructed. The structure of system dynamics models and of physical processes as they are described in the CPP are compared, and a modeling sequence integrated into a cycle of modeling and experimentation is presented. Here we also discuss how SD modeling makes use of analogies and joins physics with the wider world of learning. Finally, we present a comparison of a couple of modeling tools useful for SD modeling in physics.

Section IV introduces a short list of basic SD structures of dynamical physical systems. These structures will be found again and again in actual models. Several interesting examples of models are presented in Section V, ranging from hydraulic, electric, and thermal systems to applications in mechanics and chemistry. The examples show various features of interest in real applications.

In Section VI we will stress our belief that modeling is the activity necessary for a true understanding of physical processes. Finally, we will discuss some practical implications of SD modeling, and report observations made in our implementations of the approach (Section VII).

II The structure of theories in continuum physics

As discussed in CPP I, continuum physics has a simple structure which is visible in all fields treated in classical physics. Processes are said to be the result of the flow, the production, and the storage of certain fundamental quantities such as momentum, angular momentum, charge, entropy, mass, and amount of substance.

A theory of physics may be decomposed into four parts.[11] To see what we mean consider an example from mechanics—the motion of planets in the solar system.

1. We first have to introduce the fundamental quantities with which we describe the phenomena. Fundamental quantities are those which are not derived in terms of others. Let these be momentum, momentum flux, velocity, and mass. On the basis of these quantities new ones can be defined which may be useful for stating laws and results. Here we define the rate of change of velocity and the position in terms of velocity, and we introduce the resultant momentum flux as the sum of all momentum currents with respect to a body.
2. Now we may express our assumptions concerning the properties of momentum by stating the law of balance (Newton's law of motion), a relation involving the rate of change of momentum, and the resultant momentum flux.
3. We need constitutive laws specifying the momentum currents, and a relation between momentum and velocity. The former are given by Newton's law of gravitation—which includes the principle of action and reaction. The latter states that the velocity of a body is equal to its momentum divided by its mass. From the combination of laws presented so far, a solution, i.e., the trajectory of a planet, may be computed.
4. For the purpose of the example treated here, the last element of a theory of physics—the energy principle—is not needed. In general, however, we must make use of this principle. It relates different types of processes—electrical with thermal, thermal with mechanical, etc.—and often yields missing information in a constitutive theory.

In CPP I, a simple example of continuum thermodynamics was treated which exposed precisely the same structure. We will see that system dynamics modeling reflects this structure, leading to simple diagrams expressing our view of how nature works. In short, system dynamics modeling is a methodology for mapping—in just a couple of simple and rather intuitive steps—our basic ideas and concepts regarding physical processes onto a set of equations which can be solved to yield the evolution of the system under investigation.

III System dynamics and modeling in physics

In this section, we will discuss a number of issues related to physics and system dynamics modeling. We start by examining the role of paradigms in modeling of physical processes, show how system dynamics modeling maps the understanding of nature formed in the CPP, and discuss the structure of models and the role of modeling in general.

A. Paradigms and modeling in physics

In physics, modeling is the name of the game. Hestenes and his colleagues[10] have expressed this belief clearly in a series of important papers, and they conclude that instructional strategies should take account of the model based structure of our knowledge of the physical world.

Their claim that physics is model based should not come as a surprise. Expressions of our knowledge of the real world never are the real thing—they always constitute mental representations, i.e., models of reality, independent of the form of expression that has been chosen—word models, graphs, or formal mathematical representations.

Hestenes forcefully points out that we do not make explicit use of modeling strategies when teaching;[10] put differently, we only teach models but not modeling. He maintains that students learning physics could profit from strategies which explicitly teach the process of modeling.

How we teach this process—and how we learn physics—depends upon the concrete form taken by the mapping of reality onto abstract representations. The best known example of this mapping is the Standard Model of physics instruction (SM). It reflects a particular set of beliefs of how this transfer from reality to model should be accomplished. Since in the SM we use different paradigms for fields such as mechanics, electricity, or heat we should expect modeling to take rather different forms as well. The Continuum Physics Paradigm, on the other hand, exposes a common core structure of all fields of physics.[1] A modeling strategy based on the CPP should therefore satisfy the following requirements:

1. it must reflect the common structure of physics, and
2. the metaphor of the CPP should be mapped onto the tools used for modeling.

Moreover, it would be of great advantage if the same methodology could be applied to fields other than physics, which would greatly help to break down barriers between the different fields of human inquiry. It turns out that system dynamics modeling delivers what we need.

B. Describing physical processes the system dynamics way

In their simplest form, system dynamics tools provide just four elements from which models are constructed, irrespective of the area of application.[8] Therefore we expect a single methodology to be applicable to modeling in a science such as physics.

What is this "system dynamics way" of describing dynamical systems and processes? In short, it reflects what we know from the CPP. It allows us to put into first graphical and then mathematical form the image created in continuum physics—namely, the idea that processes are the result of the flow and the storage of certain fundamental quantities such as momentum, charge, and entropy. Obviously, this requires elements representing stored quantities (stocks), flowing quantities (flows), auxiliary quantities (converters), and connectors for building relations (Fig.1).

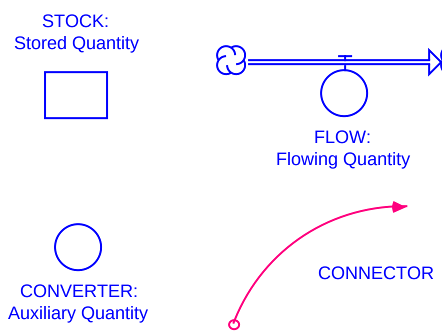


Figure 1: In Stella,[5] the four building blocks for system dynamics models are the Stock, the Flow, the Converter, and the Connector. The little clouds at the end of the Flow represent sources and sinks.

These building blocks suffice to construct the models of dynamical processes—in physics and in other sciences. Consider the following simple example. Oil from a straight-walled container flows through a long horizontal pipe at the bottom. We wish to build a model which lets us calculate the amount of oil stored in the container as a function of time.

We begin by stating the law of balance of amount of oil in the tank. The amount will be measured in terms of the volume. We know that the volume of oil can only change as a consequence of the flow of oil out of the container. This knowledge is translated into a graphical representation—a combination of a stock representing the instantaneous amount of oil inside the storage space and a flow representing the current of oil (Fig.2).

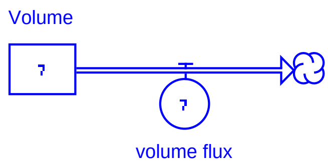


Figure 2: The combination of a stock and one or more flows represents a law of balance. In system dynamics programs, the equations of balance themselves do not have to be written; drawing them on the screen creates the mathematical representation.

The question marks tell us that two things need to be specified for a complete model: first, we have to state how much oil is in the tank at the beginning (initial value), and second, we have to determine the flow of oil expressed by the volume flux.

Next we ask ourselves which quantities the volume flux depends upon. A simple expression involves two factors: a driving force and a resistance. The driving force in the case of a volume flux is a pressure difference. Therefore we introduce these factors in the form of auxiliary quantities, and we connect them to the volume flux to state the assumption that the latter depends upon the former.

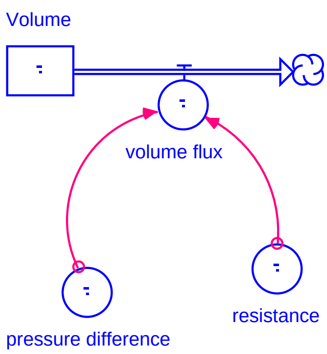


Figure 3: Specifying a flux means stating a constitutive law. Here we assume that the flux of volume depends upon the pressure difference across the pipe and a flow resistance.

Now we have to specify the new quantities. At this point we will assume the resistance to have a fixed value. The pressure difference, however, must depend upon another quantity not yet present in the model: the level of oil in the tank. This quantity, in turn, depends upon the present value of the volume of oil and the cross section of the container. All of these assumptions can be stated graphically leading to a model diagram as in Fig.4.

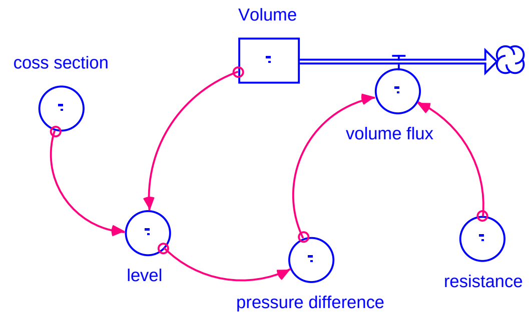


Figure 4: The complete map of the model of draining a tank. Note the feedback loop from volume to level, pressure difference, volume flux, and back to volume.

Now let us write the formal relations necessary to complete the modeling step. Note that we do not have to explicitly write down the law of balance—i.e. the differential equation involving the volume of fluid. This relation is generated automatically by drawing the combination of stock and flow(s). All the other relations, however, have to be expressed explicitly. The volume flux is assumed to be equal to the ratio of pressure difference and resistance. The pressure difference is given by the product of the level of fluid, the gravitational field, and the density of oil, while the level is determined as the ratio of volume and cross section. Finally, two parameters—the resistance and the cross section—and the initial volume have to be specified. The complete list of equations resulting from the modeling exercise is listed in Fig.5.

```
Volume(t) = Volume(t-dt) + (-volume_flux)*dt
INIT Volume = 10

volume_flux = pressure_difference/resistance

level = Volume/coss_section
pressure_difference = 800*9.81*level
resistance = 1e6
coss_section = 1
```

Figure 5: The complete list of model equations as written in Stella. The first line represents the law of balance of volume; it is generated automatically by drawing the combination of stock and flow(s). All other relations must be expressed explicitly, and parameters must be specified.

Once the equations have been introduced in the model, the question marks disappear, letting us know that the model is ready to be simulated.

The method you have witnessed here is directly transferable to other physical processes, and to systems in other fields such as biology or the social sciences. Concepts and procedures remain essentially the same.

C. The structure of system dynamics models of physical processes

Note the basic similarity between the concepts of continuum physics and a system dynamics model of a dynamical process. In the CPP, we model a process by first stating appropriate laws of balance. Then, the fluxes (or rates of production) in the laws are expressed with the help of constitutive laws. In the example treated in the previous section, there is one law of balance with a single flow, and two constitutive laws—namely, a resistance law and a capacitive law (Fig.6).

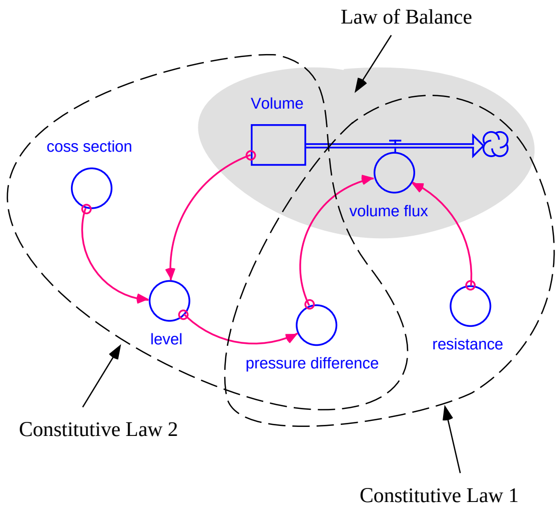


Figure 6: The map of a system dynamics model reflects the fundamental structure of a theory of (continuum) physics. Laws of balance form the backbone of the structure, and constitutive laws provide the expressions for the currents (and rates of production).

To students it is often unclear what constitutes an explanation of a process. Since we call models the explanation, the question can be rephrased: what is a model? The models we require go beyond the mere description of events and behavior found in nature and in the lab. What we want is a causal explanation of the processes. We want to know *why*, not just *how*. We want to see behind the curtain of the appearances and produce the structure made of causal links which we take as the explanation of the observed behavior. Consequently, a model exhibits the structure of a system, and behavior follows from this structure—and not vice-versa.

Naturally, we have to be specific and state what we mean by structure. In the CPP, we have a clear and unique view of what constitutes the structure of a process: it is the network of stocks and flows (laws of balance) combined with the expressions for the flows (constitutive laws) seen in system dynamics representations of dynamical systems.

D. The modeling sequence

If we only teach models—which is common in physics instruction[10]—we often begin by presenting the mathematical form of the laws which we—the teachers—know to apply to the situation at hand. Students often fail to understand the link between nature and our mathematical representation of it.

Modeling should proceed in a number of well-defined and easily visualized steps with the mathematical form of the model as the end-result, rather than the beginning. The CPP combined with system dynamics modeling naturally leads to such a sequence. We start with reality (the top layer in Fig.7) and first produce a representation in terms of the mental image provided by the CPP: processes are the result of the flow, the production, and the storage of some fundamental quantities, where the flows and rates of production depend upon the circumstances (second layer in Fig.7). Then we move on to convert the basic image into a system dynamics model map with stocks, flows, and special (feedback) relations (third layer). Finally, after providing the mathematical form of the relations first presented graphically, we arrive at the complete set of equations (fourth layer) which represents the model in a form which can be simulated.

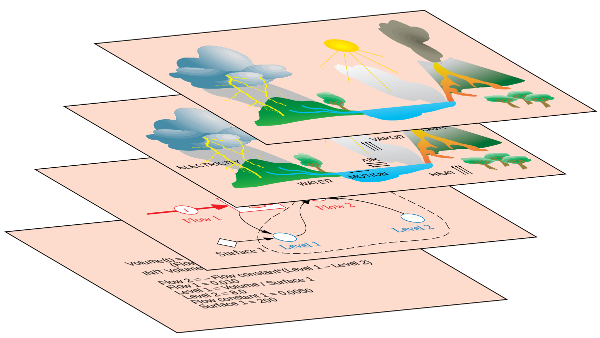


Figure 7: Modeling leads from reality to the final desired mathematical relations in a number of well-defined steps. Layers visualize different representations of reality, from the mental image created in the CPP, to system dynamics maps of the structure of systems and processes, to the final mathematical form of the model.

E. The complete modeling cycle

Measurements made in experiments and observations essentially deliver events and behavior—not models. Explanations are not forthcoming from experiments, and experimentation alone cannot yield what we need most urgently when we try to do physics.

However, it is quite clear that producing models and simulating them does not make a natural science yet. We always want to compare our view of nature to reality. If the simulation runs of models do not yield a satisfactory representation of the behavior of a system found in observations or experiments, we have to go back to the modeling step and revise the structure. We call a model a successful representation of reality only after the simulations mimic the observed behavior with sufficient accuracy. The process described is a closed modeling cycle which is traversed more than once in general.

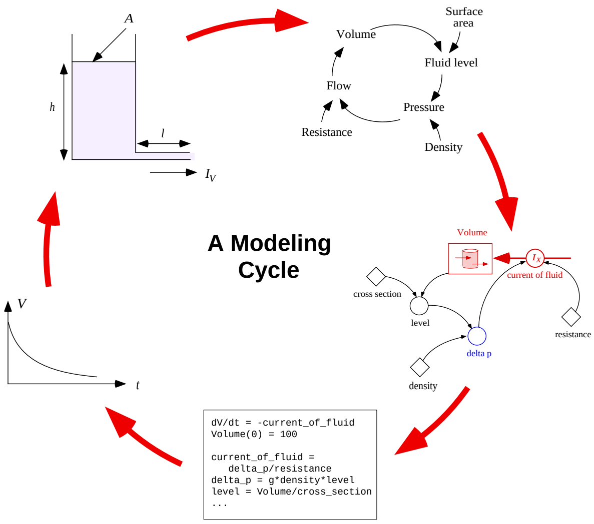


Figure 8: The complete modeling cycle is a circular procedure which leads from the observation of reality through several steps of mental representations—where the final one is in mathematical form—to simulations, and back to a comparison to observation.

F. Making use of analogies

The simplest system dynamics tools provide us with just a small number of general building blocks from which we construct the models. Since the building blocks do not refer to any particular physical system, we may expect the same elements to be useful for modeling in all fields of physics. This in turn means that there must be deep structural analogies between the fields of physics, which is indeed the case in the CPP.

The CPP therefore provides an important tool for learning. From an information theoretical view point, analogies greatly reduce the number of independent structures to be comprehended by students, leading to great economies of learning.

Making use of analogies, however, is an art in itself. It must be taught and learned. Learners must construct their understanding of the use of analogous structures. Again, a well-defined modeling sequence which is the same in all fields of physics facilitates the process.

G. Physics and the rest of the world

The use of system dynamics modeling goes far beyond physics. Since the building blocks of SD models are independent of any particular field of application, we may expect the methodology to be useful, and to take the same form, in many fields of human inquiry.

System Dynamics as it is known today is not practiced in physics very much. It is used in social sciences and management applications, in ecology, and as a learning tool in some high schools.[12] In schools it already demonstrates its power to unite fields which are separated by almost insurmountable barriers. SD modeling lends new practical meaning to the word *interdisciplinary.* Physics would profit from being a part of all of this.

H. To model or not to model…

Having access to computers—and even to modeling tools—does not automatically produce a modeling environment in physics instruction. There are many different ways one can use and abuse modeling technology which have nothing to do with modeling as such.

One positive example of using modeling technology without doing the actual modeling is playing with finished models to learn about the behavior of systems. Naturally, one should first try to learn about system behavior out there in nature and in the lab. Still, the use of models as simulations of real experiments may be of great educational value.[13]

The worst form of abuse of the new technology, on the other hand, is this. Led by teachers who have learned physics by writing down equations—which basically means all of us—students are told to look for the (differential) equation representation of the process. Then they abuse a system dynamics modeling program to "code" the equations in graphical form, and call this exercise "modeling."

Neither physics nor system dynamics deserve this kind of treatment. We should meet the challenges of physics instruction head on and find ways to teach physics using the SD modeling strategy based on the Continuum Physics Paradigm.

I. System dynamics modeling tools

Several different modeling tools are available on the market now.[5] Most system dynamics tools are very similar in appearance, sophistication, and range of application. Simulink, which builds on Matlab and is known mostly in engineering (Table 1), is an important exception.

Table 1: A comparison of Stella and Simulink

Feature	Stella	Simulink
Building blocks	4 (stock, flow, converter, and information connector)	virtually unlimited, mostly from control engineering
Functions	mathematical, statistical, control statements	mathematical, statistical, control statements
Time-discrete systems	yes	yes
Expressions	very easy to build	rather cumbersome to code
External data import	vectors of up to 2000 data points	matrices of unlimited size
Data export	ASCII table	export to Matlab
Sub-model layers	2; limited ability to handle hierarchical representations	many; good at hierarchical representation of models
Presentation of results	quick but limited graphs	sophisticated data presentation only within Matlab
Block libraries	parts of other models can be copied and imported	easy to build and maintain block libraries
Sensitivity analysis	"quick and dirty"	through programming
Programming	no provision for external functions or commands	blocks can be written in either FORTRAN or C
Numerical methods for IVPs	fixed-step Euler, Heun, and 4th order Runge Kutta methods	variable-step Runge Kutta methods; Gear method for stiff differential equations

The first tool to come out of system dynamics was Dynamo. It is a very important tool for SD research, and development of large SD models, but it is hardly useful for a first contact with modeling. As graphical computers arrived on the scene, Stella was the first to transfer the SD methodology to a user friendly environment. This apparently has made all the difference regarding the acceptance of modeling in larger sections of society. To our knowledge, there now are three major graphically oriented modeling tools with similar features.[14]

A modeling program called Madonna,[15] which does not have a graphical interface, is capable of reading Stella equations—and running them much faster than the original program. This tool may be of some use for larger models.

Simulink, a module based on Matlab, applies a rather different metaphor to represent models of dynamical systems. It transfers the diagramming technique used for analog computers to the digital arena. With its background in control engineering and signal processing, it is a strong tool in this field, with sophisticated mathematical support through Matlab. Its block library is virtually unlimited, and allows for quick coding of control structures (Table 1). Still, since the CPP is alien to this tool, it is further removed from mapping physical processes than the classic SD tools.

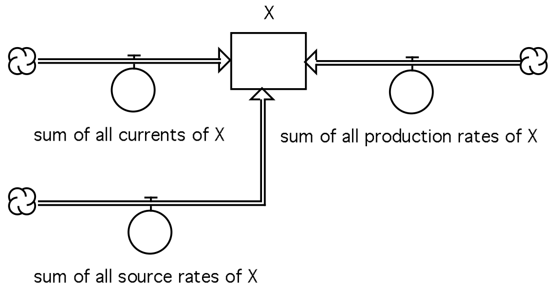
IV Generic structures

We do not suggest to teach modeling in physics by starting with these generic structures. This would be like teaching grammar before allowing children to speak their first sentences. However, they may give the reader a quick overview of basic structures of models in physics. Examples of interesting models will be given in the Section V.

A. Laws of balance

Laws of balance form the backbone of any model of dynamical processes. How we can introduce and deal with these laws has been detailed in CPP I.

A law of balance in dynamical form relates the processes—expressed in terms of the net current, source rate, and production rate of a substancelike quantities such as momentum, entropy, and charge—to the rate of change of the quantity stored in a system. In system dynamics diagrams it is expressed by connecting one or more flows to a stock (Fig.9). Doing this automatically creates a law of balance in its dynamical form. Note that a system dynamics tool such as Stella does not have different symbols for currents, sources, and production rates; rather, we use the flow for all three of them. On a purely mathematical level, in the case of lumped parameter descriptions of systems and processes, the three types of processes have the same effect upon the stored quantity.



$$\frac{dX}{dt} = I_{x,net} + \Sigma_{x,net} + \Pi_{x,net}$$

Figure 9: Laws of balance are “written” graphically by combining stocks and flows.

The flows appearing in laws of balance have to be supplied by constitutive laws. Some of these laws which occur often in the same form in different fields of physics are listed below.

B. Capacitive laws

Commonly, if the amount of a substancelike quantity X stored in a system increases, the associated level quantity—the potential φ_X—increases as well. The relation between X and φ_X, or rather between the rates of change of X and φ_X, are called capacitive laws. In most general terms, a capacity C_x is defined by

$$\dot{X} = C_x \dot{\varphi}_x \tag{1}$$

Well known examples of capacitive laws are the relation between charge, capacitance, and voltage of an electric capacitor, between momentum, mass, and velocity in translational motion, and between entropy, entropy capacity, and temperature of rigid bodies. If the capacitance is constant, the system dynamics representation of the relation is very simple (Fig.10).

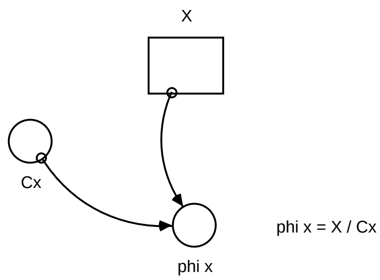


Figure 10: A capacitive law relates the potential of the quantity X to X and to the capacitance of the system.

C. Resistance laws

In dissipative flows, we may introduce a resistance to express the relation between flow and an associated potential difference:

$$I_x = \Delta\varphi_x / R_x \tag{2}$$

Again, the system dynamics diagram for this relation is very simple (Fig.11).

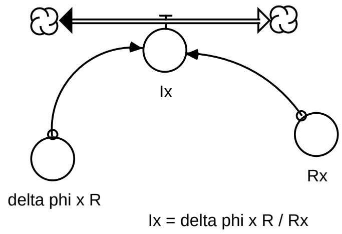


Figure 11: Resistive laws relate a flow to a driving force, i.e. an associated potential difference.

D. Inductive laws

There are laws which determine the rate of change of a quantity, rather than the quantity itself. Here, we are not thinking of laws of balance—these are altogether different—but of relations such as the law of induction, or the relation between position and speed. For example, the law of induction in hydraulics relates the rate of change of the volume flux to the inductive pressure difference (Fig.12). In general, we have

$$\Delta\varphi_x = -L\frac{dI_x}{dt} \tag{3}$$

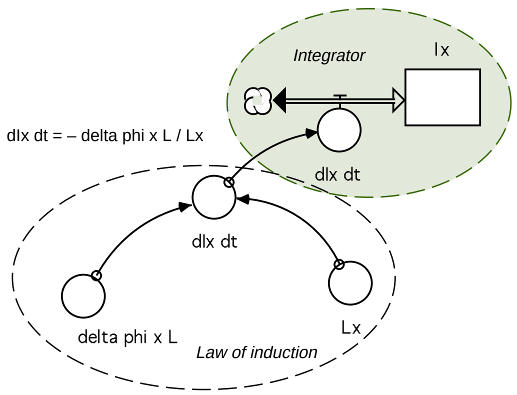


Figure 12: An inductive law yields the rate of change of a current. Since we normally want to make use of the current itself, an integrator has to be used to obtain this quantity. A tool such as Stella does not provide an integrator as such. Rather—even though it is not a law of balance—we use a flow and a stock.

E. Energy

Energy has three fundamental properties, apart from the fact that it is conserved (CPP I): it can be stored, it can flow, and it can be released (or bound). The first two properties tell us that we can use a law of balance for energy. However, what is special with energy, is the relation between flows of energy and flows of substancelike quantities such as momentum and entropy in conductive flows, and the form of the expression for the power (the rate at which energy is released or bound). The former takes the form

$$I_{Wx} = \varphi_x I_x \tag{4}$$

while the latter relation is

$$P_x = \Delta\varphi_x I_x \tag{5}$$

Both can be represented graphically (Fig.13).

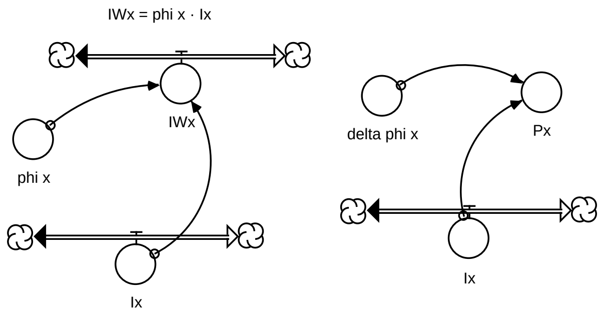


Figure 13: In conductive transports, energy is transported along with one of the substancelike quantities. If the substancelike quantity flows through a potential difference, energy is released or bound at a certain rate (called power).

V A systems zoo

Here we will present a small number of interesting modeling examples from different fields of physics. The examples have been chosen to exhibit important features of physical processes. We will briefly describe the problems and present the SD diagrams of models; in some cases, simulation results will be presented. Providing the equations may be an interesting—and probably not very difficult—exercise for the reader. The models may be obtained from the author in electronic form.[16]

A. Hydraulics as a door to dynamical systems

Consider the flow of a highly viscous fluid from one tank into another. The tanks have straight walls, and they are joined at the bottom by a horizontal pipe. The model presented here solves the problem of how the levels of the fluid adjust to the same height in the course of time.

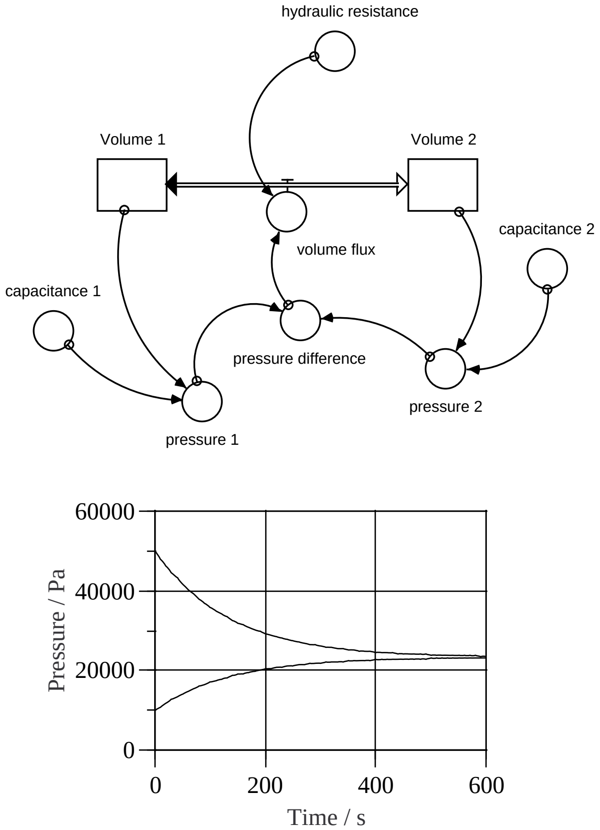


Figure 14: The problem of the flow of a highly viscous fluid through a pipe joining two straight-walled tanks. The reader should try to identify the generic structures present in the model diagram, and to provide concrete equations for the model.

B. Electric circuits with branches

The second example introduces two interesting features: inductive behavior and the problem of dealing with the balance of charge flowing into and out of a node. Consider a simple circuit containing a capacitor and a resistor in parallel. These elements are connected to an inductive element as shown in Fig.15.

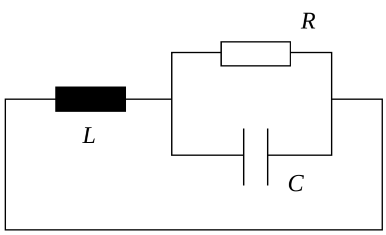


Figure 15: Circuit diagram showing the electric elements. The part of the circuit containing the inductor is open at the beginning.

Initially, the capacitor having a capacitance of 1.0 μF has a voltage of 10 V. The inductance is 1.0 mH, while the resistance has a value of 1.0 Ω. The part of the circuit containing the inductor is open. At the initial moment it is closed. We wish to calculate the currents and the voltages as a function of time.

Naturally, many more questions can be asked about the behavior of the circuit, such as what is the rate of change of the current through the inductor at certain points in time, or how much energy has been released in the resistor during a certain period. To answer the latter question we may extend the model to include the calculation of quantities of energy.

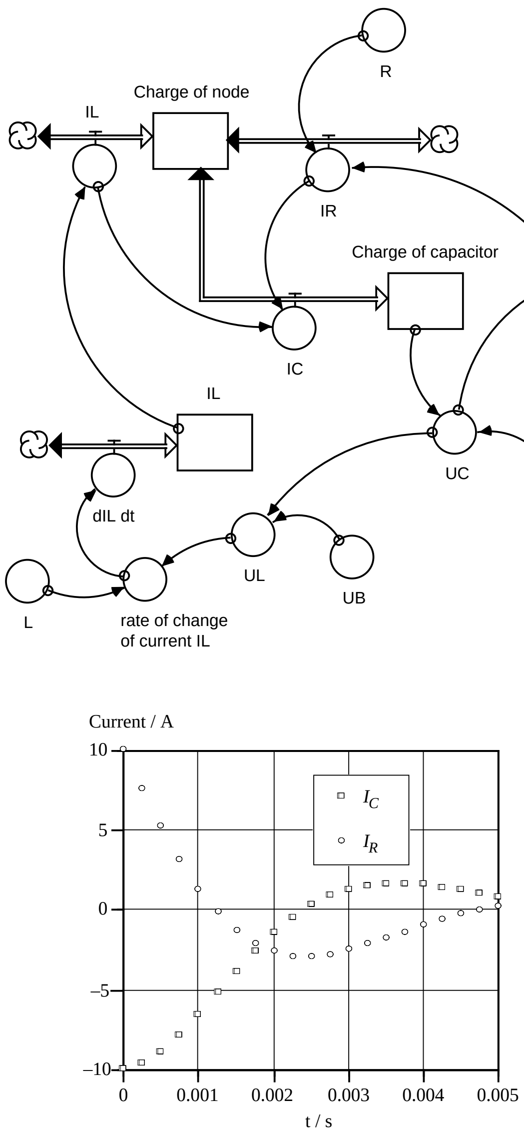


Figure 16: The model diagram for the circuit of Fig.15. Note how a law of balance for a node can be formulated. Since a node does not store any charge, the sum of the three currents must be zero. Knowing two of them, the third can be calculated. The lower graph shows the currents through the capacitor and the resistor as functions of time, respectively.

C. A solar collector as an environmental system

Consider a solar collector for heating air. This is a thermal dynamical system which responds to the environment as well as to its own structure. Air is pumped at a certain rate through a rectangular duct, where the surface is the solar absorber. We wish to calculate the temperatures of the absorber and the air as a function of time, and at the same time we want to determine all irreversibilities and compute the overall rate of production of entropy.[11]

We use the law of balance of entropy (Fig.17). The absorber and the air are treated as separate homogenous bodies, which means that their heating proceeds reversibly. Entropy is produced as a result of four irreversible processes: (1) entropy flow from the absorber to the air, (2) entropy flow from the absorber to the ambient, (3) absorption of radiation, (4) mixing of cold air with the air in the collector. As an example, consider the last of the processes and its rate of production of entropy:

$$\Pi_{s,mixing} = c_p I_m \left[\ln\left(\frac{T_{air}}{T_{air,in}} \right) - \frac{1}{T_{air}} \left(T_{air} - T_{air,in} \right) \right] \quad \textbf{(6)}$$

Here, I_m is the mass flux of air.

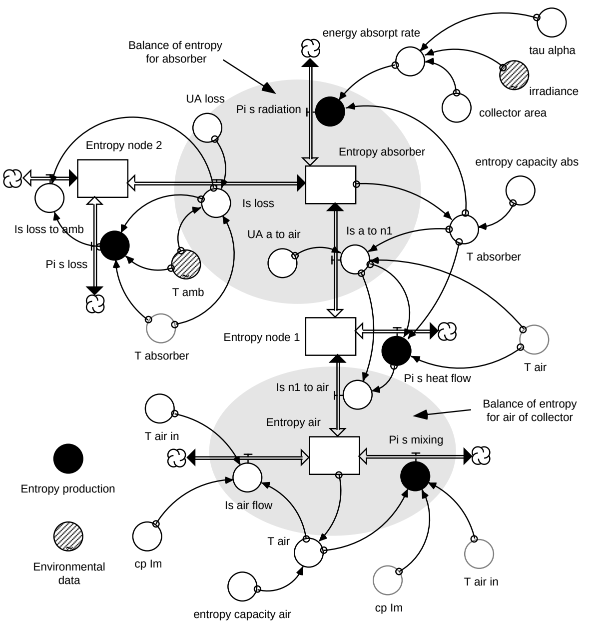


Figure 17: Note the two laws of balance of entropy for the absorber and the air, respectively (gray areas). The nodes are introduced to represent "thermal resistors" for heat flow with corresponding rates of production of entropy (black circles). Entropy is also produced in the absorber and the air as a result of absorption and of mixing. Environmental data, such as the irradiance and the ambient temperature, are introduced as vectors (hatched circles). Is: entropy flux; Pi s: rate of entropy production; UA: energy transfer coefficient; amb: ambient.

The model may be used, among others, to perform a thermal optimization by minimizing the entropy produced during operation of the system. The parameter to be varied is the mass flux.

D. Transport and change of chemical species

The ozone problem furnishes and interesting application of the transport and the reactions of chemical substances. Here, the problem of transport and reaction are treated as spatially separate: we have a transport of CFCs from the factory to the upper atmosphere where the molecules react and add to the depletion of ozone (Fig.18).

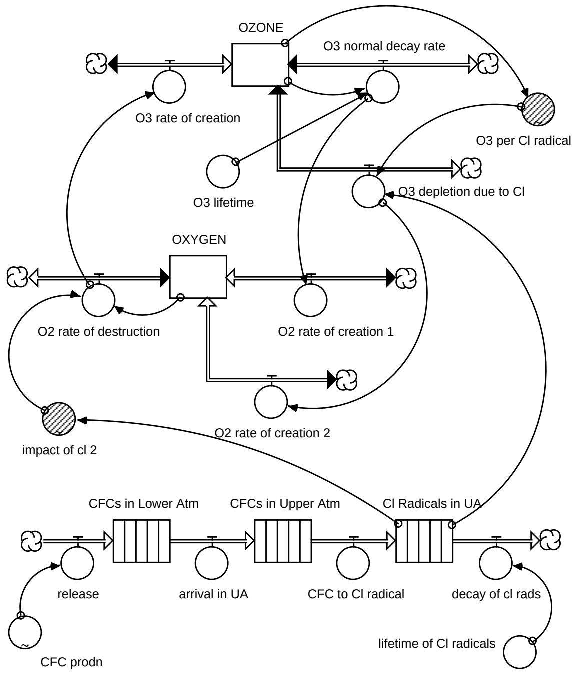


Figure 18: Model of the transport of CFCs from the factory to the upper atmosphere, and reactions between O2 and ozone. Note the hatched stocks which mimic the action of "conveyor belts" for the transport of species. The reactions are modeled in terms of the balance of amounts of O2 and O3, respectively. The impact of Cl radicals from CFCs in the upper atmosphere is taken into account by simple graphical relations between the variables (hatched converters). The model was adapted from one created by High Performance Systems, Inc.[5]

E. Open systems: rocket motion

Open systems with variable mass nicely demonstrate that Newton's second law in its classic form does not go all the way to solve problems in mechanics.[17] Creating a SD model of rocket motion, we make use of the fundamental laws of balance of momentum and mass (Fig.19). Except for the speed, which is of fundamental importance, the kinematic quantities only appear on the side-line as derived from the speed. Besides demonstrating the relations visibly, using tools such as Stella also let us treat the problem without resorting to calculus. In particular, we do not have to know how to build the derivative of momentum; in the SD model the speed of the rocket is calculated simply as the ratio of the instantaneous values of momentum and mass. We can also deal with a variable mass flux and observe its impact on the acceleration of the rocket.

Models such as this one are easily extended to other situations such as vertical rocket motion with air resistance. Forces on the rocket are included as additional momentum fluxes in the law of balance of momentum, and quantities such as the gravitational field and air density can be made to depend upon the vertical position of the body.

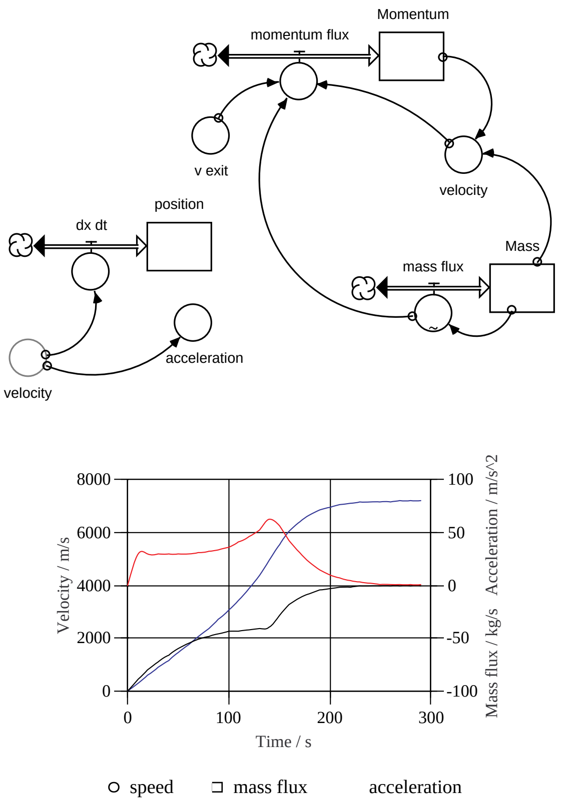


Figure 19: SD model diagram and solution of rocket problem. The model makes use of the laws of balance of momentum and mass of the rocket. The kinematic quantities are calculated from the velocity.

F. Using the energy principle

The energy principle is used to relate different processes to one another. If the rate at which energy is released in one process can be calculated, we can equate it to the rate at which energy is bound in the follow up process. As an example consider a car. During breaking the motor acts on a pressure vessel having a piston. The air in the vessel is compressed, and it stores energy. The energy can be released again as the air expands, driving the piston which in turn drives the wheels. In the SD model in Fig.20 we introduce the laws of balance of angular momentum and of volume of air (volume is created and destroyed in the process of expansion and compression of the air, respectively). The flux of angular momentum (i.e., the torque) and the production rate of volume are related through energy.

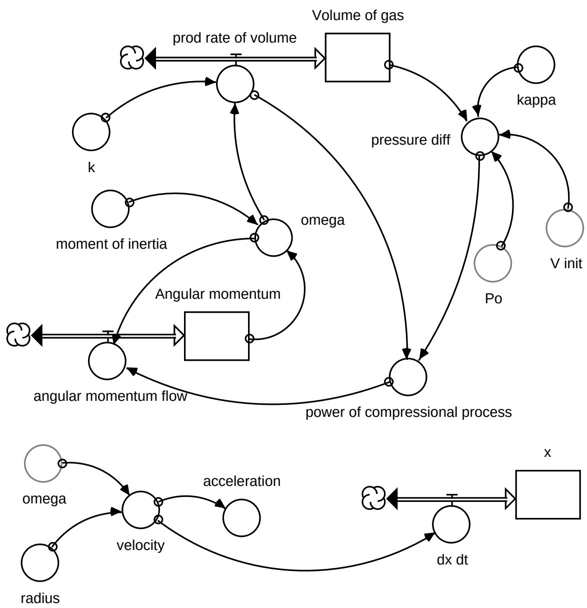
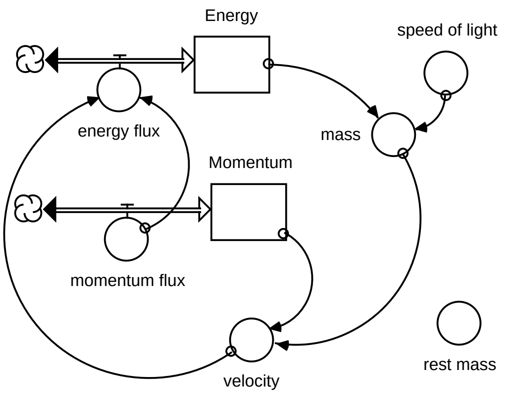


Figure 20: Energy storage in a pressure vessel may be used to save energy of cars. Note the fundamental structures (the laws of balance of angular momentum and volume of air), and how the constitutive laws for the flux of angular momentum and the production rate of volume are related via the power of the processes. The compression of the air follows the adiabatic law.

G. Relativistic motion

Commonly, students have difficulty understanding the kinematic side of special relativity, i.e. the relations between space and time. Relativistic dynamics, on the other hand, builds on the laws known from newtonian mechanics if we only add the well-known relation between energy and mass.

Assume we specify the rest mass of a body, and the force acting upon it. The law of balance of momentum again is the starting point of our investigation (Fig.21). Force (momentum flux) and momentum have the same meaning in relativity as in classical mechanics. The speed of the body is the ratio of the instantaneous values of momentum and mass, again as in non-relativistic physics. Now, the speed and the momentum flux determine the associated flux of energy with respect to the body; the flux is the product of velocity and momentum flux. Again we have used a basic relation already known from classical physics. Knowing the energy flux we can calculate the energy from the law of balance of energy. The energy finally yields the mass of the body, and we have completed the model (Fig.21). As before, we do not have to make recourse to rules of calculus to obtain our relations.




```
Energy(t) = Energy(t - dt) + (energy_flux) * dt
INIT Energy = speed_of_light^2*rest_mass
energy_flux = velocity*momentum_flux

Momentum(t) = Momentum(t - dt) + (momentum_flux) * dt
INIT Momentum = 0
momentum_flux = 100

mass = Energy/(speed_of_light^2)
velocity = Momentum/mass

rest_mass = 1
speed_of_light = 3e8
```

Figure 21: The model for the problem of linear relativistic motion. We make use of the laws of balance of momentum and energy, and the mass-energy relation. Note the form of the equations as they are assembled in Stella.

H. Extended systems and finite elements: the wave guide

So far all the examples presented models of spatially uniform systems. SD modeling, however, lets us also deal with spatially continuous systems in a simple and special way.

Consider a wave guide. Electromagnetic waves pass through the guide. The phenomenon is the result of the interplay of storage and conduction of charge, where the transport is both conductive and inductive. We simply divide the wave guide into a number of elements each of which we treat as a uniform body having the properties of capacitance, inductance, and resistance. Each element stores charge, and the charge flows from the center of an element to center of the next.

The model starts with the law of balance of charge for each of the elements (Fig.22). The electric potential (voltage to ground) of an element is calculated with the help of the capacitance of the element. The voltage between the elements is the cause of the conductive transport and the inductive change of the currents. The law of induction yields the rate of change of the current which, when integrated, yields the current (Fig.16). After constructing the model for a single element, we simply copy it and connect the copy to the first element, and so forth. This produces a special kind of finite element model of the one-dimensional wave guide (Fig.22). It may be employed, for example, to investigate the speed of propagation of waves, and the influence of the conductance of the material.

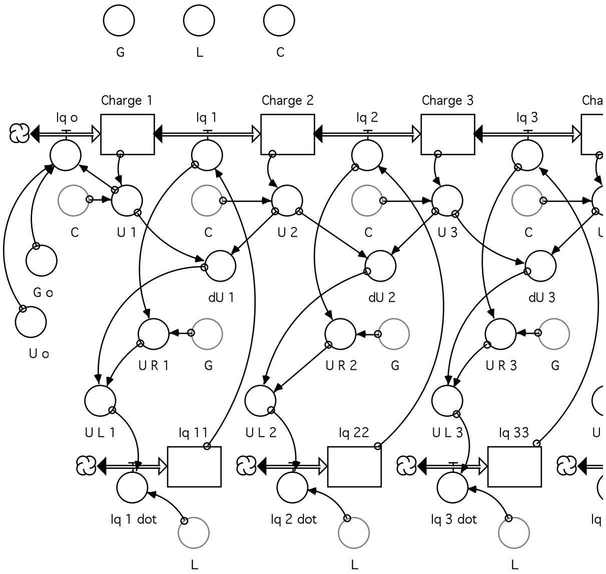


Figure 22: A system dynamics finite element model of a one-dimensional wave guide. The wave guide is divided into sections, and each section is modeled as a spatially uniform body. Note the similarity of a part of the model for a section with the model of Fig.16. By defining the voltage at one end (U_o) as a pulse, we can observe the progress of the pulse through the wave guide and determine its speed. In the diagram, I_q stands for a current of electric charge, U denotes the voltage, and C, L, and G stand for capacitance, inductance, and conductance, respectively.

VI Modeling and understanding

Modeling is the name of the game, and the model is the explanation. Therefore it would seem that we should create models if we want to understand physical processes.

Actually, there is nothing new about this statement. We always teach models when we teach physics. However, many times the models are woefully inadequate as the following well-known example shows. To demonstrate the action of inertia, we can use a heavy block suspended from a thin string (Fig.23). We attach another thin thread at the bottom, and pull on it either hard or very slowly.

Depending on how we do this, the lower or the upper thread will break.

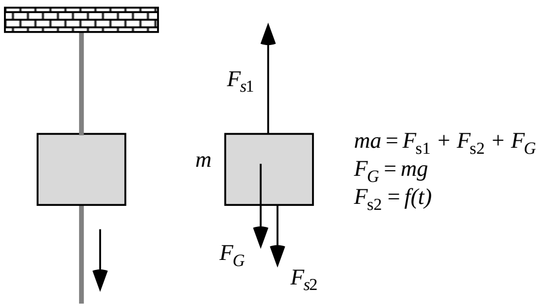


Figure 23: A block suspended from the ceiling, free body diagram, and the equations describing the system.

Attributing the observed effects to the inertia of the suspended block already constitutes a model. However, it does not explain much at all. We could then resort to our usual analysis known from introductory Newtonian mechanics and produce the appropriate equations describing the system (Fig.23). Inspecting them shows that they still do not answer the question of why things happen as they do. Prescribing the force with which we pull on the lower string as a function of time is not sufficient to compute the tension in the upper string, precisely since the effect of inertia of the block cannot be determined. The explanation fails.

An explanation must make use of the elastic (or plastic) properties of the strings. We could model them as ideal springs which break as the momentum current through them becomes too large. It should not bee all too difficult to set up the system dynamics model of the system of a block and two springs (Fig.24). We make use of the law of balance of momentum for the block and introduce the three momentum fluxes due to gravity and the springs. In the model diagram of Fig.24, the springs are represented as inductive mechanical elements responding to a speed difference. Instead of prescribing the force with which we pull on the lower string, we specify the speed with which we move the lower end of the lower spring downward. A constant factor *k* allows for changing this speed (Fig.24). Pulling quickly means the factor is high.

Simulation of the model with a small and a large factor, respectively, shows that in the former case the tension in the upper string is always larger than that in the lower one by an amount which is roughly the weight of the body (Fig.24); therefore, the upper string reaches the critical tension earlier than the lower one. If we pull fast, on the other hand, the tension in the lower string quickly overtakes that of the upper thread; it will break earlier. Here we clearly see the action of inertia (i.e. the momentum capacitance) of the body: the momentum supplied through the lower string does not flow fast enough through the body to reach the upper string. Inertia as momentum capacitance shows its effect in delaying the flow of momentum through the upper string.

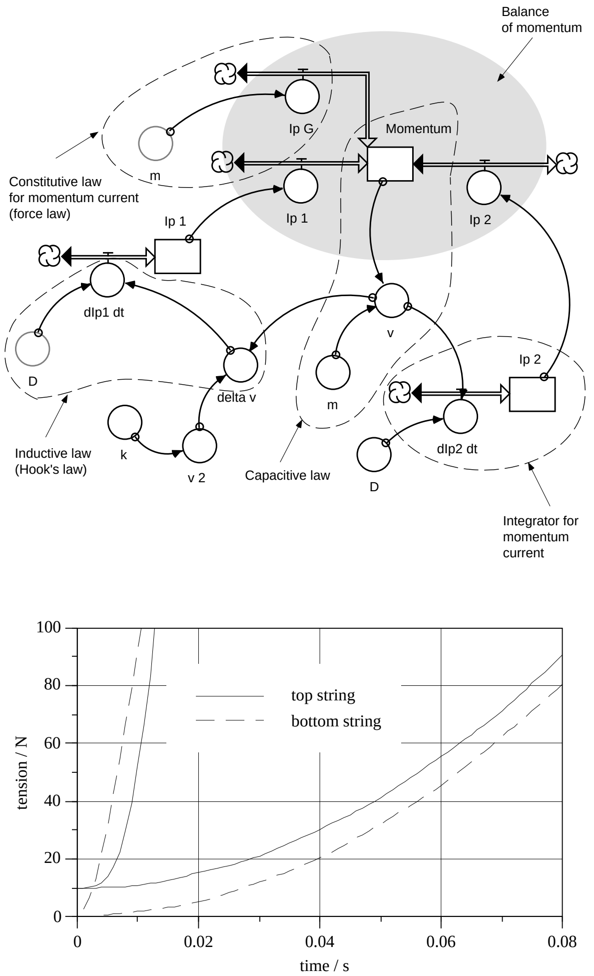


Figure 24: System dynamics model diagram of a block suspended from an ideal spring. We pull on the block using a second spring. Note that the springs have been modeled as inductors where the inductance is the inverse of the spring constant *D*. If we pull slowly (small value of *k*), the tension in the upper spring is always larger than that in the lower one. Pulling fast, on the other hand, quickly lets the tension in the lower spring surpass that in the upper one. The critical value for breaking is reached earlier by the upper or the lower string depending on how we pull.

VII Modeling, teaching, and learning

We have argued already in CPP I why we propose to change the fundamental paradigm upon which we build the introductory physics course. In the current paper we have demonstrated the relation between this paradigm and SD modeling in physics. We should finally address the question if SD modeling can actually change the *form* of learning physics, and maybe lead to improvements in the learning process.

The modeling approach detailed in this paper can be applied in many different ways in physics courses, from a superficial demonstration of SD modeling and SD tools to making it the foundation of a (lab based) course. Here we will briefly present what we have done so far in our courses, and discuss some important questions.

A. Integrating experimental and modeling labs

Recent developments in physics education have included new forms of introductory college courses which are more or less lab based. We just mention Activity Based Physics,[18] and the CUPLE Physics Studio.[19] Especially the Physics Studio format shows how lecture, lab, and recitation can be replaced by an integrated physics course which seems to have great merit.

SD modeling is perfectly suited for activity based and integrated physics courses and it could be put at the center of learning and teaching. Independent of the degree of use, SD modeling should be integrated with the experimental lab, student-teacher interaction, and the use of modern interactive media and the classic text book, including problem solving.

Modeling should be a lab (or studio) activity. This enables us to combine modeling with the comparison of model behavior and real behavior—either through observations in nature or measurements in experiments—to complete the modeling cycle of Fig.8. The latest form of our integrated lab lets students work two hours every two weeks for a year on a small number of medium sized projects (Table 2) which always involve experiments (possibly including the design of data acquisition strategies), model construction, model consumption (simulation), comparison of measurements and modeled behavior, model refinement, and so forth.

So far we have kept the format of teaching physics in small classes, with about 20 to 25% of the time spent in still smaller groups in the lab. In recent years we have changed the lab part of the course by integrating experiments with modeling activities. While this is far from what may be achieved in the future with the entire course centering around the modeling activity, first results of the modest attempts are encouraging. Apart from the obvious attraction of using computers in today's learning environments, students' reactions support the claim that modeling leads to a different quality of the learning process, and that the integration of modeling with experiments greatly increases motivation for—and understanding of—what it is we are doing in a physics course. Students mention that seeing relations put into the form of model diagrams greatly aids in understanding physics problems and the process of solving them; that being able to model real life problems much more easily increases their interest in their work; and that modeling the behavior of systems actually observed in the lab leads to still better appreciation of foundations and the applications of physics.

Table 2: Examples of experimental and modeling projects

Field	Description of project
Electricity	Charging and discharging of capacitors.
Thermal	Pouring hot water into a thick-walled container. Heating and evaporating water.
Hydraulics	Capacitive, resistive, and inductive effects in discharging a container.
Translation	Collisions of model trains with different types of shock absorbers. Bungee jumping.
Rotation	Torsional pendulum with damping and harmonic driving.

B. Solving physics problems using SD models

There is a further use of modeling not mentioned so far: it can be employed in problem solving if we allow for a slight reformulation of problems and the process of solving them.

As the normal physics problems have been constructed to let students solve problems without needing access to (computer) modeling, they ask only those questions which can be answered directly. Creating SD models of dynamical processes, on the other hand, stresses finding the structure of the problem rather than the answer to a particular question. In SD models, answers must be read from the model runs.

Actually, using SD modeling in problem solving teaches us how to approach paper and pencil questions as well. It teaches us not to look so much for the answer to the question posed, but to first determine what is going on in the system described, and then to write down the relations for the processes which have been identified.

The typical physics problems can be added to modeling and model consumption activities: we can ask questions the modelers must answer, questions which strongly resemble classic problem sets. Put differently, a physics course which makes use of modeling may profit from a redesign of at least some of the usual end of chapter questions and problems. We may wish to have a part of the problems replaced by those which are posed as part of the simulation exercises during modeling activities.

C. Modeling, learner centered learning, and constructing one's knowledge

All that has been said so far indicates that SD modeling can lead to strong learner centered learning strategies. Modeling simply should not be left to lectures. If we only talk about modeling we will never achieve its potential. Fortunately, the tools available today are so simple and powerful that whatever may have been true in the past—that the actual process of modeling dynamical systems is too difficult for students—isn't true any longer.

On the other hand, SD modeling activities may serve as the source of the construction of understanding—in the constructivist sense of the word. Constructing models is obviously what is required of anyone learning physics. Therefore, if we really let students do this on their own we may hope that they will be able not only to be active but also to *construct their own knowledge*.

VIII Summary: Learning physics through SD modeling?

If we take the claim of SD modeling serious—namely that it leads to a well organized and easily visualized modeling process for all types of dynamical systems—we should attempt to make modeling aided by physical process thinking the starting point of learning and teaching physics. Our own activities at Winterthur are a far cry from what may be possible in the future.

There is strong evidence that the combination of the CPP and system dynamics modeling can lead to a new and improved physics course at different levels of the curriculum. Learning through modeling activities is a distinct possibility brought to us by a combination of a clearer understanding of the structure of laws of physics and easy-to-use tools for putting this understanding into the form of models which can be simulated.

At TWI we have an environment which is particularly conducive to our developments. As future engineers, our students see how physics can be applied in their fields particularly through the modeling of dynamical processes. Indeed, our still timid efforts at introducing modeling very early in the education of engineers have greatly increased the use of modeling in engineering courses and project and thesis work which follow after the introductory courses.

However, we believe that much of our experience with student reactions can be transferred to other settings. Indeed, we have been teaching a section on physics as part of a general graduate course on system dynamics modeling. The participants come from many different fields. So far we have had sociologists and economists, business people, management consultants, and engineers, chemists, physicists, and ecologists taking part. The section on physics is purely modeling based; there is no standard course with lecture and lab. It is interesting to see that these people, many of whom have had some physics years or decades ago in high school—where they feared it—take to physics and integrate it into their knowledge from the point of view of somebody interested in dynamical systems.

Our engineering students also realize that the modeling approach can be used not just in physics and engineering, but also in fields ranging from other natural sciences all the way to the social sciences and management. Seeing the relation between different fields of human activity brings advantages our students don't want to miss once they have been exposed to this view.

Acknowledgments

Special thanks to Werner Maurer, Martin Simon, Regula Keller, and my students, who have all participated in the construction of system dynamics models of physical processes, and whose experience has increased my knowledge of how to apply SD modeling within the Continuum Physics Paradigm of physics instruction.

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Cambridge, MA, 1968). J.Forrester, *Urban Dynamics* (MIT Press, Cambridge, MA, 1969).

5 There are several programs available commercially, which let us create models of dynamical systems in a simple manner. The best known system dynamics tools are: Stella (High Performance Systems, Inc., Hanover, NH; http://www.hps-inc.com), Dynamo (Pugh-Roberts Associates, Cambridge MA), Powersim (Powersim AS, Isdalsto, Norway; http://www.powersim.no), and Vensim (Ventana Systems, Inc., Belmont MA; http://www.std.com/vensim). A modern tool used in engineering which has some similarity with system dynamics programs is Simulink (The Mathworks, Inc., Natick, MA; http://www.mathworks.com).

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11 H.U. Fuchs, *The Dynamics of Heat* (see Footnote 2).

12 CC-STADUS Project (http://www.teleport.com/~sguthrie/cc-stadus.html). The MIT System Dynamics in Education Project provides much material on using system dynamics in education on the Internet (http://sysdyn.mit.edu/sdep.html).

13 W.E. Boyce et. al., "Interactive multimedia modules in mathematics, engineering, and science." Computers in Physics **11**,151-156, Mar/Apr 1997.

14 These are Stella, Powersim, and Vensim. See Footnote 4.

15 Madonna. See http://www.kagi.com/madonna. Until now, there only are Macintosh versions of Madonna available.

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