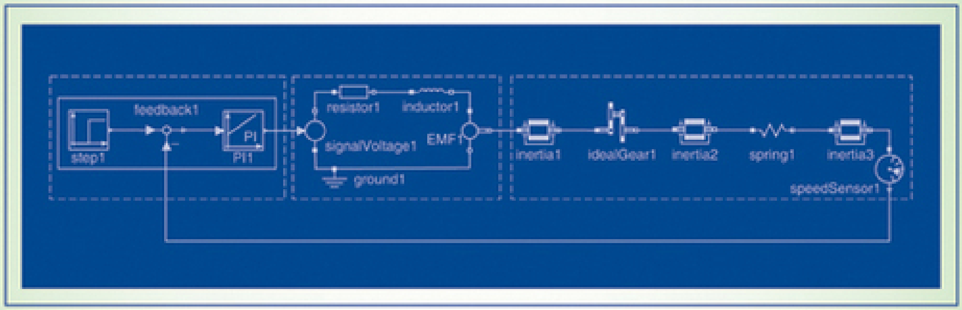
Introduction to

Modeling and Simulation of Technical and Physical Systems *with* Modelica®



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Preface

This book teaches the basic concepts of modeling and simulation and gives an introduction to the Modelica language to people who are familiar with basic programming concepts. It gives a basic introduction to the concepts of modeling and simulation, as well as the basics of object-oriented component-based modeling for the novice. The book has the following goals to be:

- A useful textbook in introductory courses on modeling and simulation.
- Easily accessible for people who do not previously have a background in modeling, simulation and object orientation.
- A basic introduction of the concepts of physical modeling, object-oriented modeling, and component-based modeling.
- A demonstration of modeling examples from a few selected application areas.

The book contains examples of models in a few different application domains, as well as examples combining several domains.

All examples and exercises in this book are available in an electronic self-teaching material called DrModelica, based on this book and the more extensive book *Principles of Object-Oriented Modeling of Simulation with Modelica 2.1* Fritzson (2004), for which an updated version is planned. DrModelica gradually guides the reader from simple introductory examples and exercises to more advanced ones. Part of this teaching material can be freely downloaded from the book's website, www.openmodelica.org, where additional (teaching) material related to this book can be found.

ACKNOWLEDGEMENTS

The members of the Modelica Association created the Modelica language and contributed many examples of Modelica code in the Modelica Language Rationale and Modelica Language Specification (see http://www.modelica.org), some of which are used in this book. The members who contributed to various versions of Modelica are mentioned further below.

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Linköping, Sweden PETER FRITZSON
May 2011

CHAPTER 1

Basic Concepts

It is often said that computers are revolutionizing science and engineering. By using computers we are able to construct complex engineering designs such as space shuttles. We are able to compute the properties of the universe as it was fractions of a second after the big bang. Our ambitions are ever-increasing. We want to create even more complex designs such as better spaceships, cars, medicines, computerized cellular phone systems, and the like. We want to understand deeper aspects of nature. These are just a few examples of computer-supported modeling and simulation. More powerful tools and concepts are needed to help us handle this increasing complexity, which is precisely what this book is about.

This text presents an object-oriented component-based approach to computer-supported mathematical modeling and simulation through the powerful Modelica language and its associated technology. Modelica can be viewed as an almost universal approach to high-level computational modeling and simulation, by being able to represent a range of application areas and providing general notation as well as powerful abstractions and efficient implementations. The introductory part of this book, consisting of the first two chapters, gives a quick overview of the two main topics of this text:

- Modeling and simulation
- The Modelica language

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The two subjects are presented together since they belong together. Throughout the text Modelica is used as a vehicle for explaining different aspects of modeling and simulation. Conversely, a number of concepts in the Modelica language are presented by modeling and simulation examples. The present chapter introduces basic concepts such as *system, model*, and *simulation*. Chapter 2 gives a quick tour of the Modelica language as well as a number of examples, interspersed with presentations of topics such as object-oriented mathematical modeling. Chapter 3 gives an introduction to the Modelica class concept, whereas Chapter 4 introduces modeling methodology for continuous, discrete, and hybrid systems. Chapter 5 gives a short overview of the Modelica Standard Library and some currently available Modelica model libraries for a range of application domains. Finally, in two of the appendices, examples are presented of textual modeling using the OpenModelica electronic book OMNotebook tool, as well as very simple graphical modeling.

1.1 SYSTEMS AND EXPERIMENTS

What is a system? We have already mentioned some systems such as the universe, a space shuttle, and the like. A system can be almost anything. A system can contain subsystems that are themselves systems. A possible definition of system might be:

- A system is an object or collection of objects whose properties we want to study.

Our wish to study selected properties of objects is central in this definition. The "study" aspect is fine despite the fact that it is subjective. The selection and definition of what constitutes a system is somewhat arbitrary and must be guided by what the system is to be used for.

What reasons can there be to study a system? There are many answers to this question but we can discern two major motivations:

- Study a system to understand it in order to build it. This is the engineering point of view.
- Satisfy human curiosity, for example, to understand more about nature—the natural science viewpoint.

1.1.1 Natural and Artificial Systems

A system according to our previous definition can occur naturally, for example, the universe, it can be artificial such as a space shuttle, or a mix of both. For example, the house in Figure 1.1 with solar-heated warm tap water is an artificial system, that is, manufactured by humans. If we also include the sun and clouds in the system, it becomes a combination of natural and artificial components.

Even if a system occurs naturally, its definition is always highly selective. This is made very apparent in the following quote from Ross Ashby (1956, p. 39):

> *At this point, we must be clear about how a* system *is to be defined. Our first impulse is to point at the* pendulum *and to say "the system is that thing there." This method, however, has a fundamental disadvantage: every material object contains no less than an infinity of variables, and therefore, of possible systems. The real pendulum, for instance, has not only length and position; it has also mass, temperature, electric conductivity, crystalline structure, chemical impurities, some radioactivity, velocity, reflecting power, tensile strength, a surface film of moisture, bacterial contamination, an optical absorption, elasticity, shape, specific gravity, and so on and on. Any suggestion that we should study all the facts is unrealistic, and actually the attempt is never made.*

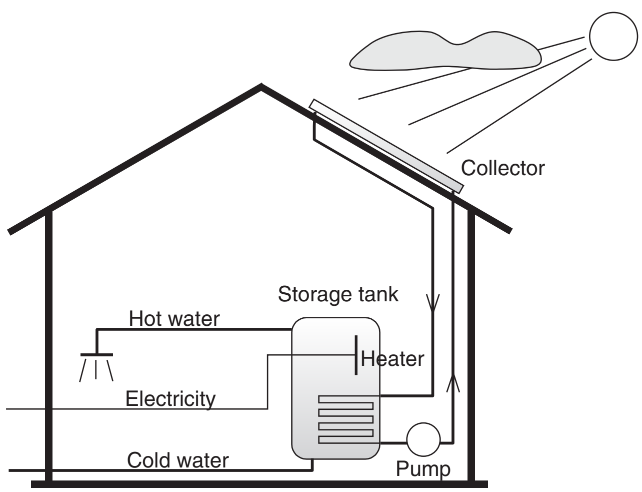

Figure 1.1 A system: a house with solar-heated warm tap water, together with clouds and sunshine.

What is necessary is that we should pick out and study the facts that are relevant to some main interest that is already given.

Even if the system is completely artificial, such as the cellular phone system depicted in Figure 1.2, we must be highly selective in its definition, depending on what aspects we want to study for the moment.

An important property of systems is that they should be *observable*. Some systems, but not large natural systems like the universe, are also *controllable* in the sense that we can influence their behavior through inputs, that is:

- The *inputs* of a system are variables of the environment that influence the behavior of the system. These inputs may or may not be controllable by us.
- The *outputs* of a system are variables that are determined by the system and may influence the surrounding environment.

In many systems the same variables act as *both inputs and outputs*. We talk about *acausal* behavior if the relationships or influences between variables do not have a causal direction, which is the case for relationships described by equations. For example, in a mechanical system the forces from the environment influence the displacement of an object, but on the other hand the displacement of the object influences the forces between the object and environment. What is input and what is output in this case is primarily a choice by the observer, guided by what is interesting to study, rather than a property of the system itself.

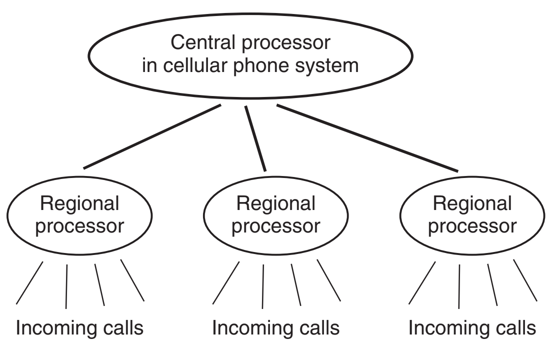

Figure 1.2 Cellular phone system containing a central processor and regional processors to handle incoming calls.

1.1.2 Experiments

Observability is essential in order to study a system according to our definition of system. We must at least be able to observe some outputs of a system. We can learn even more if it is possible to exercise a system by controlling its inputs. This process is called *experimentation*, that is:

- An *experiment* is the process of extracting information from a system by exercising its inputs.

To perform an experiment on a system, it must be both controllable and observable. We apply a set of external conditions to the accessible inputs and observe the reaction of the system by measuring the accessible outputs.

One of the disadvantages of the experimental method is that for a large number of systems many inputs are not accessible and controllable. These systems are under the influence of inaccessible inputs, sometimes called *disturbance inputs*. Likewise, it is often the case that many really useful possible outputs are not accessible for measurements; these are sometimes called *internal states* of the system. There are also a number of practical problems associated with performing an experiment, for example:

- The experiment might be too *expensive*: Investigating ship durability by building ships and letting them collide is a very expensive method of gaining information.
- The experiment might be too *dangerous*: Training nuclear plant operators in handling dangerous situations by letting the nuclear reactor enter hazardous states is not advisable.
- The *system* needed for the experiment might *not yet exist*. This is typical of systems to be designed or manufactured.

The shortcomings of the experimental method led us to the model concept. If we make a model of a system, this model can be investigated and may answer many questions regarding the real system if the model is realistic enough.

1.2 THE MODEL CONCEPT

Given the previous definitions of system and experiment, we can now attempt to define the notion of model:

- A *model* of a system is anything an "experiment" can be applied to in order to answer questions about that *system*.

This implies that a model can be used to answer questions about a system *without* doing experiments on the *real* system. Instead we perform simplified "experiments" on the model, which in turn can be regarded as a kind of simplified system that reflects properties of the real system. In the simplest case a model can just be a piece of information that is used to answer questions about the system.

Given this definition, any model also qualifies as a system. Models, just like systems, are hierarchical in nature. We can cut out a piece of a model, which becomes a new model that is valid for a subset of the experiments for which the original model is valid. A model is always related to the system it models and the experiments to which it can be subjected. A statement such as "a model of a system is invalid" is meaningless without mentioning the associated system and the experiment. A model of a system might be valid for one experiment on the model and invalid for another. The term model *validation*, see Section 1.5.3, always refers to an experiment or a class of experiment to be performed.

We talk about different kinds of models depending on how the model is represented:

- *Mental* model—a statement like "a person is reliable" helps us answer questions about that person's behavior in various situations.
- *Verbal* model—this kind of model is expressed in words. For example, the sentence "More accidents will occur if the speed limit is increased" is an example of a verbal model. Expert systems is a technology for formalizing verbal models.
- *Physical* model—this is a physical object that mimics some properties of a real system, to help us answer questions about that system. For example, during design of artifacts such as

buildings, airplanes, and so forth, it is common to construct small physical models with the same shape and appearance as the real objects to be studied, for example, with respect to their aerodynamic properties and aesthetics.

- *Mathematical* model—a description of a system where the relationships between variables of the system are expressed in mathematical form. Variables can be measurable quantities such as size, length, weight, temperature, unemployment level, information flow, bit rate, and so forth. Most laws of nature are mathematical models in this sense. For example, Ohm's law describes the relationship between current and voltage for a resistor; Newton's laws describe relationships between velocity, acceleration, mass, force, and the like.

The kinds of models that we primarily deal with in this book are mathematical models represented in various ways, for example, as equations, functions, computer programs, and the like. Artifacts represented by mathematical models in a computer are often called *virtual prototypes*. The process of constructing and investigating such models is virtual prototyping. Sometimes the term *physical modeling* is used also for the process of building mathematical models of physical systems in the computer if the structuring and synthesis process is the same as when building real physical models.

1.3 SIMULATION

In the previous section we mentioned the possibility of performing "experiments" on models instead of on the real systems corresponding to the models. This is actually one of the main uses of models, and is denoted by the term *simulation*, from the Latin *simulare*, which means to pretend. We define a simulation as follows:

- A *simulation* is an experiment performed on a model.

Analogous to our previous definition of *model*, this definition of simulation does not require the model to be represented in mathematical or computer program form. However, in the rest of this text we will concentrate on *mathematical models*, primarily those that have