Modelica™ - A Unified Object-Oriented Language for Physical Systems Modeling

Version 1

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1. Introduction

There definitely is an interoperability problem amongst the large variety of modeling and simulation environments available today, and it gets more pressing every year with the trend towards ever more complex and heterogeneous systems to be simulated. The main cause of this problem is the absence of a state-of-the-art, standardized external model representation. Modeling languages, where employed, often do not adequately support the structuring of large, complex models and the process of model evolution in general. This support is usually provided by sophisticated graphical user interfaces - an approach which is capable of greatly improving the user´s productivity, but at the price of specialization to a certain modeling formalism or application domain, or even uniqueness to a specific software package. It therefore is of no help with regard to the interoperability problem.

Among the recent research results in modeling and simulation, two concepts have strong relevance to this problem:

- *Object oriented modeling languages* already demonstrated how object oriented concepts can be successfully employed to support hierarchical structuring, reuse and evolution of large and complex models independent from the application domain and specialized graphical formalisms.
- *Non-causal modeling* demonstrated that the traditional simulation abstraction -the input/output block- can be generalized by relaxing the causality constraints, i.e., by not committing ports to an 'input' or 'output' role early, and that this generalization enables both more simple models and more efficient simulation while retaining the capability to include submodels with fixed input/output roles.

Examples of object-oriented and/or non-causal modeling languages include: ASCEND, Dymola, gPROMS, NMF, ObjectMath, Omola, SIDOPS+, Smile, U.L.M., ALLAN, and VHDL-AMS.

The combined power of these concepts together with proven technology from existing modeling languages justifies a new attempt at introducing interoperability and openness to the world of modeling and simulation systems.

Having started as an action within ESPRIT project "Simulation in Europe Basic Research Working Group (SiE-WG)" and currently operating as Technical Committee 1 within Eurosim, a working group made up of simulation tool builders, users from different application domains, and computer scientists has made an attempt to unify the concepts and introduce a common modeling language. This language, called *Modelica,* is intended for modeling within many application domains (for example: electrical circuits, multi-body systems, drive trains, hydraulics, thermodynamical systems and chemical systems) and possibly using several formalisms (for example: ODE, DAE, bond graphs, finite state automata and Petri nets). Tools which might be general purpose or specialized to certain formalism and/or domain will store the models in the Modelica format in order to allow exchange of models between tools and between users. Much of the Modelica syntax will be hidden from the end-user because, in most cases, a graphical user interface will be used to build models by selecting icons for model components, using dialogue boxes for parameter entry and connecting components graphically.

The work started in the continuous time domain since there is a common mathematical framework in the form of differential-algebraic equations (DAE) and there are several existing modeling languages based on similar ideas. There is also significant experience of using these languages in various applications. It thus seems to be appropriate to collect all knowledge and experience and design a new unified modeling language or neutral format for model representation. The short range goal was to design a modeling language for differential-algebraic equation systems with some discrete event features to handle discontinuities and sampled systems. The design should be extendible in order that the goal can be expanded to design a multi-formalism, multi-domain, general-purpose modeling language. This is a report of the design state as of September 1997, Modelica version 1.0.

The object-oriented, non-causal modeling methodology and the corresponding standard model representation, Modelica, should be compared with at least four alternatives. Firstly, established commercial *general purpose simulation tools*, such as ACSL, EASY5, SIMULINK, System Build and others, are continually developed and Modelica will have to offer significant practical advantages with respect to these. Secondly, *special purpose simulation programs* for electronics (Spice, Saber, etc), multibody systems (ADAMS, DADS, SIMPACK, etc), chemical processes (ASPEN Plus, SpeedUp, etc) have specialized GUI and strong model libraries. However, they lack the multi-domain capabilities. Thirdly, many industrial simulation studies are still done without the use of any general purpose simulation tool, but rather relying on *numerical subroutine libraries and traditional programming languages*. Based on experience with present tools, many users in this category frequently doubt that any general purpose method is capable of offering sufficient efficiency and robustness for their application. Forthly, an IEEE supported *alternative language standardization effort* is underway: VHDL-AMS.

Most engineers and scientists recognize the advantages of an expressive and standardized modeling language. Unlike a few years ago, they are today ready to sacrifice reasonable amounts of short-term advantages for the benefit of abstract things like potential abundance of compatible tools, sound model architecture, and future availability of ready-made model libraries. In this respect, the time is ripe for a new standardization proposal. Another significant argument in favor of a new modeling language lies in recent achievements by present languages using a *non-causal* modeling paradigm. In the last few years, it has in several cases been proved that non-causal simulation techniques not only compare to, but outperform special purpose tools on applications that are far beyond the capability of established block oriented simulation tools. Examples exist in multi-body and mechatronics simulation, building simulation, and in chemical process plant simulation. A combination of modern numerical techniques and computer algebra methods give rise to this advantage. However, these non-causal modeling and simulation packages are not general enough, and exchange of models between different packages is not possible, i.e. a new unified language is needed. Furthermore, text books promoting the object-oriented, non-causal methodology are now available, such as Cellier (1991), and university courses are given in many countries.

The next section will give an introduction to the basic concepts of Modelica by means of a small example. Requirements for this type of language are then discussed. Section 4 is the main section and it gradually introduces the constructs of Modelica and discusses the rationale behind them. It is followed by an overview of present object-oriented equation based modeling languages that have been used as a basis for the Modelica language design. The design rationale from a computer science point of view is given in section 6. Syntax and detailed semantics as well as the Modelica standard library are presented in the appendices.

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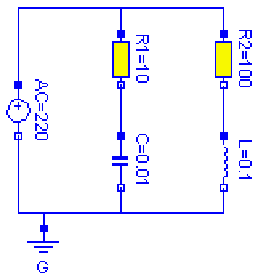
2. Modelica at a Glance

To give an introduction to Modelica we will consider modeling of a simple electrical circuit as shown below.



The system can be broken up into a set of connected electrical standard components. We have a voltage source, two resistors, an inductor, a capacitor and a ground point. Models of these components are typically available in model libraries and by using a graphical model editor we can define a model by drawing an object diagram very similar to the circuit diagram shown above by positioning icons that represent the models of the components and drawing connections.

A Modelica description of the complete circuit looks like

```
model circuit
  Resistor  R1(R=10);
  Capacitor C(C=0.01);
  Resistor  R2(R=100);
  Inductor  L(L=0.1);
  VsourceAC AC;
  Ground    G;

equation
  connect (AC.p, R1.p);    // Capacitor circuit
  connect (R1.n, C.p);
  connect (C.n, AC.n);
  connect (R1.p, R2.p);    // Inductor circuit
  connect (R2.n, L.p);
  connect (L.n,  C.n);
  connect (AC.n, G.p);     // Ground
end circuit;
```

For clarity, the definition of the graphical layout of the composition diagram (here: electric circuit diagram) is not shown, although it is usually contained in a Modelica model as annotations (which are not processed by a Modelica translator and only used by tools). A composite model of this type specifies the topology of the system to be modeled. It specifies the components and the connections between the components. The statement

```
Resistor R1(R=10);
```

declares a component `R1` to be of class `Resistor` and sets the default value of the resistance, `R`, to 10. The connections specify the interactions between the components. In other modeling languages connectors are referred as cuts, ports or terminals. The language element **connect** is a special operator that generates equations taking into account what kind of quantities that are involved as explained below.

The next step in introducing Modelica is to explain how library model classes are defined.

A connector must contain all quantities needed to describe the interaction. For electrical components we need the quantities voltage and current to define interaction via a wire. The types to represent them are declared as

```
type Voltage = Real(unit="V");
```

```
type Current = Real(unit="A");
```

where `Real` is the name of a predefined variable type. A real variable has a set of attributes such as unit of measure, initial value, minimum and maximum value. Here, the units of measure are set to be the SI units.

In Modelica, the basic structuring element is a **class**. There are seven *restricted* classes with specific names, such as **model**, **type** (a class which is an extension of built-in classes, such as **Real**, or of other defined types), **connector** (a class which does not have equations and can be used in connections). For a valid model it is fully equivalent to replace the **model**, **type**, and **connector** keywords by the keyword **class**, because the restrictions imposed by such a specialized class are fulfilled by a valid model.

The concept of restricted classes is advantageous because the modeller does not have to learn several different concepts, but just one: the class concept. All properties of a class, such as syntax and semantic of definition, instantiation, inheritance, genericity are identical to all kinds of restricted classes. Furthermore, the construction of Modelica translators is simplified considerably because only the syntax and semantic of a **class** has to be implemented along with some additional checks on restricted classes. The basic types, such as `Real` or `Integer` are built-in **type** classes, i.e., they have all the properties of a class and the attributes of these basic types are just parameters of the class.

There are two possibilities to define a class: The standard way is shown above for the definition of the electric circuit (**model** circuit). A short hand notation is possible, if a new class is identical to an existing one and only the default values of attributes are changed. The types above, such as *Voltage*, are declared in this way.

A connector class is defined as

```
connector Pin
  Voltage      v;
  flow Current i;
end Pin;
```

A connection **connect** `(Pin1, Pin2)`, with `Pin1` and `Pin2` of connector class `Pin`, connects the two pins such that they form one node. This implies two equations, namely `Pin1.v = Pin2.v` and `Pin1.i + Pin2.i = 0`. The first equation indicates that the voltages on both branches connected together are the same, and the second corresponds to Kirchhoff's current law saying that the currents sum to zero at a node (assuming positive value while flowing into the component). The sum-to-zero equations are generated when the prefix flow is used. Similar laws apply to flow rates in a piping network and to forces and torques in mechanical systems.

When developing models and model libraries for a new application domain, it is good to start by defining a set of connector classes. A common set of connector classes used in all components in the library supports compatibility of the component models.

A common property of many electrical components is that they have two pins. This means that it is useful to define an "interface" model class,

```
partial model TwoPin "Superclass of elements with two electrical pir
  Pin p, n;
  Voltage v;
  Current i;
equation
  v = p.v - n.v;
  0 = p.i + n.i;
```

```
  i = p.i;
end TwoPin;
```

that has two pins, `p` and `n`, a quantity, `v`, that defines the voltage drop across the component and a quantity, `i`, that defines the current into the pin `p`, through the component and out from the pin `n`. The equations define generic relations between quantities of a simple electrical component. In order to be useful a constitutive equation must be added. The keyword **`partial`** indicates that this model class is incomplete. The key word is optional. It is meant as an indication to a user that it is not possible to use the class as it is to instantiate components. Between the name of a class and its body it is allowed to have a string. It is treated as a comment attribute and is meant to be a documentation that tools may display in special ways.

To define a model for a resistor we exploit `TwoPin` and add a definition of parameter for the resistance and Ohm's law to define the behavior:

```
model Resistor "Ideal electrical resistor"
  extends TwoPin;
  parameter Real R(unit="Ohm") "Resistance";
equation
    R*i = v;
end Resistor;
```

The keyword **parameter** specifies that the quantity is constant during a simulation run, but can change values between runs. A parameter is a quantity which makes it simple for a user to modify the behavior of a model.

A model for an electrical capacitor can also reuse the TwoPin as follows:

```
model Capacitor "Ideal electrical capacitor"
  extends TwoPin;
  parameter Real C(unit="F") "Capacitance";
equation
    C*der(v) = i;
end Capacitor;
```

where **`der`**`(v)` means the time derivative of `v`. A model for the voltage source can be defined as

```
model VsourceAC "Sin-wave voltage source"
  extends TwoPin;
  parameter Voltage VA = 220 "Amplitude";
  parameter Real f(unit="Hz") = 50  "Frequency";
  constant  Real PI=3.141592653589793;
equation
  v = VA*sin(2*PI*f*time);
end VsourceAC;
```

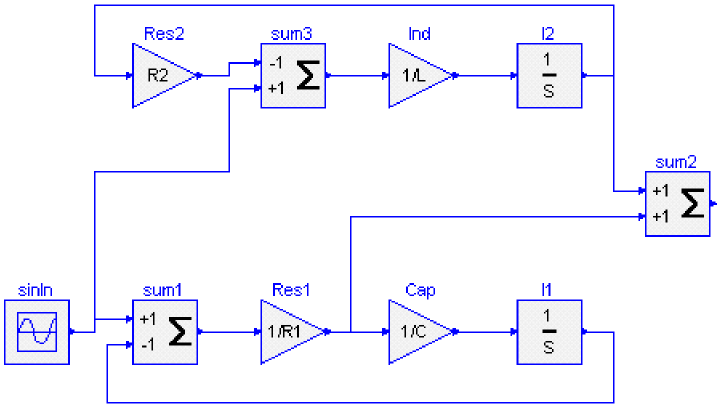
In order to provide not too much information at this stage, the constant `PI` is explicitly declared, although it is usually imported from the Modelica standard library (see appendix). Finally, we must not forget the ground point.

```
model Ground "Ground"
  Pin p;
equation
  p.v = 0;
end Ground;
```

The purpose of the ground model is twofold. First, it defines a reference value for the voltage levels. Secondly, the connections will generate one Kirchhoff's current law too many. The ground model handles this by introducing an extra current quantity `p.i`, which implicitly by the equations will be calculated to zero.

Comparison with block oriented modeling

If the above model would be represented as a block diagram, the physical structure will not be retained as shown below. The block diagram is equivalent to a set of assignment statements calculating the state derivatives. In fact, Ohm's law is used in two different ways in this circuit, once solving for i and once solving for u.



This example clearly shows the benefits of physically oriented, *non-causal modeling* compared to block oriented, causal modeling.

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3. Requirements for Multi-domain Modeling

In this section, the most important requirements used for the Modelica language design are collected together.

The Modelica language should support both ODE and DAE (differential-algebraic equations) formulations of models. The mixture of DAE and discrete events should be possible and be defined in such a way that efficient simulation can be performed. Other data types than real, such as integer, Boolean and string should be supported. External functions written in common programming languages need to be supported in addition to a data type corresponding to external object references. It should be possible to express information about units used and minimum and maximum allowed values for a variable in order that a modeling tool might do consistency checking. It should be possible to parameterize models with both values of certain quantities and also with respect to model representation, i.e., allowing, for example, to select different levels of detail for a model. Component arrays and the connection of elements of such arrays should be supported. In order to allow exchange of models between different tools, also a certain standardization of graphical attributes for icon definitions and object diagrams should be done within the Modelica definition.

Certain modeling features will be added in later stages of the Modelica design. One example is to allow partial differential equations. More advanced discrete event modeling facilities will also be considered then, for example to allow queue handling and dynamical creation of model instances.

Besides requirements for modeling in general, every discipline has its specific peculiarities and difficulties which often require special consideration. In the following sections, such requirements from multiple domains are presented.

Block Diagrams

Block diagrams consist of input/output blocks. For the definition of linear state space systems and transfer functions *matrices* and *matrix equations* are needed. This is most conveniently done with a MATLAB-like notation.

It is also important to support fixed and variable *time delays*. This could be done by calling an external function which interpolates in past values. However, if a delay is defined via a specific language construct, it is in principle possible to use a specific integrator to take care of the delay which can be done in a better numerical way than in the first case. Therefore, a delay operator should be defined in the language which leaves the actual implementation to the Modelica translator. Furthermore, interpolation in 1-, 2-, n-dimensional *tables* with fixed and variable grids has to be supported, because technical models often contain tables of measured data.

If it is known that a component is an input/output block, *local analysis* of the equations is possible which improves the error diagnostics considerably. For example, it can be detected whether the number of unknown variables of the block matches the number of equations in the block. Therefore, it should be possible to state explicitly that a model component is an input/output block.

Multi-Body Systems

Multi-body systems are used to model 3-dimensional mechanical systems, such as robots, satellites and vehicles. Nearly all variables in multi-body system modeling are vectors or matrices and the equations are most naturally formulated as matrix equations. Therefore, support of matrices is essential. This should include the **cross** operator for the vector cross-product because this operation often occurs in mechanical equations. It is convenient to have multi-body objects with several interfaces, but without requiring that every interface has to be connected for a model. For example, revolute and prismatic joints should have an additional interface to attach a drive train to drive the joint.

Usually, multi-body algorithms are written in such a way that components cannot be connected together in an arbitrary way. To ensure that an erroneous connection cannot be created, it should be possible to define *rules* about the connection structure. Rules help to provide a meaningful error message as early as possible.

In order that Modelica will be attractive to use for modeling of multi-body systems, *efficiency* is crucial. It must be possible that Modelica generated code is as efficient as that of special purpose multi-body programs. For that, operators like **symmetric** and **orthogonal** are necessary in order to be able to state that a matrix is symmetric or orthogonal, respectively.

Electrical and Electronic Circuits

Models of different complexity to describe electrical components are often needed. Therefore, it should be easy to *replace* a specific model description of a component by another one in the model of an electrical circuit.

It might be advantageous to implement complicated elements, such as detailed transistor models, by procedural code. This may be either an external C or C++ function or a Modelica function. In any case, the model equations are already sorted and are not expanded, i.e., every instance uses the same "function call". This is especially important, if a large number of instances are present.

It is essential that SPICE net list descriptions of electrical circuits can be used within Modelica, because vendor models of electric hardware components are described in this format. It seems sufficient to provide the SPICE component models as classes in a Modelica library and to rely on an external tool which transforms a SPICE net list description into a composite Modelica model.

Besides non-linear simulation, *small signal analysis* is often needed for electrical circuits. This implies linearization and frequency response calculation. Numerical linearization introduces unnecessary errors. For electrical circuits it is almost always possible to symbolically differentiate the components. Special language constructs are probably not needed because in principle Modelica translators can be realized which derive the (symbolically) linearized components automatically. Modern electric circuit programs use symbolic Jacobians to enhance the efficiency. Similar to linearization, it should be possible to compute the symbolic Jacobian from a Modelica model by symbolic differentiation. If a component is provided as external function, it should be possible to provide an external function for the corresponding Jacobian of the component as well.

Chemical and Thermodynamic Systems

Processing systems for chemical or energy production are often composed of complex structures. The modeling of these systems needs encapsulation of detailed descriptions and abstraction into hierarchies in order to handle the complexity. To increase the reuse of submodels in complex structures there is a need for an advanced concept of parameterization of submodels. Especially, component arrays and class parameters are needed. An example is a structure parameter for the change of the number of trays in a distillation plant.

In order to achieve a high degree of model reuse, all medium specific data and calculation should be encapsulated in a medium properties submodel. In most cases the thermodynamic properties of the medium will be calculated externally by one of the many available specialized software packages. Thus it is necessary to provide a calling interface to external functions in ordinary programming languages. Keeping in mind both efficient simulation and model reuse, there should be a uniform way how thermodynamic properties of different external packages can be accessed from Modelica models.

Many applications in process engineering and power plant simulation can only be captured adequately with distributed parameter models. A method of lines (MOL) grid discretisation (either finite difference, finite volume or finite element methods) is the state of the art of all but a few very specialized simulation packages for modeling partial differential equations (PDEs). Modelica is envisaged as a language that is both open to future advances in numerical techniques and as an exchange format for many existing software environments. Existing simulation environments should be able to simulate Modelica code after preprocessing to DAE form. Support for PDE is planned for future versions of Modelica.

Energy domain systems

Simulation in the energy domain sector is mainly used for improving or designing technical systems: boilers, kilns, HVAC systems, pressure governors, etc. The first characteristic of these systems is that they are complex and multi-domain. For example the building energy domain deals with all types of heat exchanges, with fluid flows, with combustion, with particle pollution, with system controls, automatons etc. Modelica needs to address all these issues. It stresses the need for non-causal hierarchical modeling. To a certain extent temperature distribution and PDE are relevant for improvement studies. Matrices and PDE features are useful. Combustion models need to address thermodynamic tables by means of a suitable feature. But, the main requirements of this domain are linked with user-friendliness, reuse, documentation, capitalization for study efficiency and reproducibility. This means that it is necessary to isolate models, isolate numerical data, isolate validation runs, integrate validity checks (domains, constraints, units, etc.) and in order to produce automatic documentation include documentation features.

Bond graphs

Bond graphs (Karnopp and Rosenberg, 1968; Breedveld, 1985) are designed to model the *energy flow* of physical systems using a small set of unified modeling primitives, such as storage, transformation and dissipation of (free) energy. Bond graphs are in principle labeled and directed graphs, in which the vertices represent submodels and the edges represent an ideal energy connection between power ports. This connection is a point-to-point connection, i.e. only one bond can be connected to a power port. When preparing for simulation, the bonds are embodied as two-signal connections with opposite directions. This signal direction depends on both the internal description of the submodel and the structure of the bond graph where the submodel is used; it is an algorithmic process. Consequently, the model equations are non-causal. Within some submodel equations, the power directions of the connected bonds are used in generating the proper equations. As a consequence, it must be possible to define *rules* about the connection structure, especially that only *one-to-one* connections are possible. Furthermore, it must be possible to inquire the *direction* of a connection in a component, in order that the *positive* energy flow direction can be deduced. Since bond graphs can be mixed with block-diagram parts, bond-graph submodels can have power ports, signal inputs and signal outputs as their interfacing elements. Furthermore, aspects like the physical domain of a bond (energy flow) can be used to support the modeling process, and should therefore be incorporated in Modelica. Note that the power bonds can be *multi dimensional*, i.e., are composed of a matrix of single power bonds. This *multi-bond* feature is used to describe, e.g., 3D mechanical systems in an elegant and compact way.

Finite Automata and Extensions

Finite automata are used to model discrete systems, such as discrete control devices as well as switching structure of clutches or idealized thyristors. Several extensions are popular, e.g., Petri nets, grafcet and state charts. It seems more flexible and powerful to build component libraries of e.g., Petri nets and state charts, using basic Modelica language constructs instead of having direct built-in language elements. Besides basic event handling, realization requires *multi-assignment* statements: When the token of a Petri Net is removed from a place and moved to one or more other places, the whole operation has to be treated as one non-separable operation. Furthermore, several equations for the same variable are present because the state (or number of tokens) of a place can be switched off from all transitions which are connected to this place (several assignments to the same variable, but performed at different events).

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4. Modelica Language Rationale and Overview

Modeling the dynamic behavior of physical systems implies that one is interested in specific properties of a limited class of systems. These restrictions give a means to be more specific then is possible when focusing on systems in general. Therefore, the physical background of the models should be reflected in Modelica.

Nowadays, physical systems are often complex and span multiple physical domains, whereas mostly these systems are computer controlled. Therefore, hierarchical models (i.e., models described as connected submodels) using properties of the physical domains involved should easily be described in Modelica. To properly support the modeler (i.e. to be able to perform automated modeling), these physical properties should be incorporated in Modelica in such a way, that checking consistency, like checking against basic laws of physics, can be programmed easily in the Modelica translators. Examples of physical properties are the physical quantity and the physical domain of a variable. This implies that a suitable representation for physical systems modeling is more than a set of pure mathematical differential equations.

4.1 Basic Language Elements

The language constructs will be developed gradually starting with small examples, and then extended by considering practical issues when modeling large systems.

Handling large models means careful structuring in order to reuse model knowledge. A model is built-up from

- basic components such as Real, Integer, Boolean and String
- structured components, to enable hierarchical structuring
- component arrays, to handle real matrices, arrays of submodels, etc
- equations and/or algorithms (= assignment statements)
- connections
- functions

Some means of declaring variable properties is needed, since there are different kinds of variables, Parameters should be given values and there should be a possibility to give initial conditions.

Basic declarations of variables can be made as follows:

```
Real u, y(start=1);
parameter Real T=1;
```

Real is the name of a predefined class or type. A Real variable has an attribute called `start` to give its initial value. A component declaration can be preceded by a *specifier* like **constant** or **parameter** indicating that the component is constant, i.e., its derivative is zero. The specifier parameter indicates that the value of the quantity is constant during simulation runs. It can be modified when a component is reused and between simulation runs. The component name can be followed by a *modification* to change the value of the component or its attributes.

Equations are composed of expressions both on the left hand side and the right hand side like in the following filter equation.

```
equation
T*der(y) + y = u;
```

Time derivative is denoted by **der**( ).

4.2 Classes for Reuse of Modeling Knowledge

Assume we would like to connect two filters in series. Instead of repeating the filter equation, it is more convenient to make a definition of a filter once and create two instances. This is done by declaring a *class*. A class declaration contains a list of component declarations and a list of equations preceded by the keyword **equation**. An example of a low pass filter class is shown below.

```
class LowPassFilter
  parameter Real T=1;
  Real u, y(start=1);

equation
  T*der(y) + y = u;
end LowPassFilter;
```

The model class can be used to create two instances of the filter with different time constants and "connecting" them together as follows

```
class FiltersInSeries
  LowPassFilter F1(T=2), F2(T=3);

equation
  F1.u = sin(time);
  F2.u = F1.y;
end FiltersInSeries;
```

In this case we have used a *modification* to modify the time constant of the filters to T=2 and T=3 respectively from the default value T=1 given in the low-pass filter class. Dot notation is used to reference components, like u, within structured components, like F1. For the moment it can be assumed that all components can be reached by dot-notation. Restrictions of accessibility will be introduced later. The independent variable is referenced as **time**.

If the FiltersInSeries model is used to declare components at a higher hierarchical level, it is still possible to modify the time constants by using a hierarchical *modification:*

```
model ModifiedFiltersInSeries
  FiltersInSeries F12(F1(T=6), F2(T=11));
end ModifiedFiltersInSeries;
```

The class concept is similar as in programming languages. It is used for many purposes in Modelica, such as model components, connection mechanisms, parameter sets, input-output blocks and functions. In order to make Modelica classes easier to read and to maintain, special keywords have been introduced for such special uses, **model**, **connector**, **record**, **block**, **type** and **package**. It should be noted though that the use of these keywords only apply certain restrictions, like records are not allowed to contain equations. However, for a valid model, the replacement of these keywords by **class** would give exactly the same model behavior. In the following description we will use the specialized keywords in order to convey their meaning.

Records

It is possible to introduce parameter sets as *record*s which is a restricted form of class which may not have any equations:

```
record FilterData
  Real T;
end FilterData;

record TwoFilterData
  FilterData F1, F2;
end TwoFilterData;

model ModifiedFiltersInSeries
  TwoFilterData TwoFilterData1(F1(T=6), F2(T=11));
```

```
    FiltersInSeries F12=TwoFilterData1;
  end ModifiedFiltersInSeries;
```

The modification `F12=TwoFilterData1` is possible since all the components of `TwoFilterData1 (F1, F2, T) are` present in `FiltersInSeries`. More about type compatibility can be found in section 4.4.

Packages

Class declarations may be nested. One use of that is maintenance of the name space for classes, i.e., to avoid name clashes, by storing a set of related classes within an enclosing class. There is a special kind of class for that, called **package**. A package may only contain declarations of constants and classes. Dot-notation is used to refer to the inner class. Examples of packages are given in the appendix where the Modelica standard package is described which is always available for a Modelica translator.

Information Hiding

So far we have assumed all components to be accessible from the outside by dot-notation. To develop libraries in such a way is a bad principle. Information hiding is essential from a maintenance point of view.

Considering the FiltersInSeries example, it might be a good idea to just declare two parameters for the time constants, T1 and T2, the input, u and the output y as accessible from the outside. The realization of the model, using two instances of model LowPassFilter, is a protected detail. Modelica allows such information hiding by using the heading **protected**.

```
model FiltersInSeries2
  parameter Real T1=2, T2=3;
  input u;
  output y;

protected
  LowPassFilter F1(T=T1), F2(T=T2);

equation
  F1.u = u;
  F2.u = F1.y;
  y = F2.y;
end FiltersInSeries2;
```

Information hiding does not control interactive environments though. It is possible to inspect and plot protected variables. Note, that variables of a **protected** section of a class A can be accessed by a class which **extends** class A. In order to keep Modelica simple, additional visibility rules present in other object-oriented languages, such as *private* (no access by subtypes), are not used.

4.3 Connections

We have seen how classes can be used to build-up hierarchical models. It will now be shown how to define physical connections by means of a restricted class called **connector**.

We will study modeling of a simple electrical circuit. The first issue is then how to represent pins and connections. Each pin is characterized by two variables, voltage and current. A first attempt would be to use a connector as follows.

```
connector Pin
  Real v, i;
end Pin;
```

and build a resistor with two pins p and n like

```
model Resistor
  Pin p, n;        // "Positive" and "negative" pins.
  parameter Real R "Resistance";

equation
    R*p.i = p.v - n.v;
    n.i = p.i;     // Assume both n.i and p.i to be positive
                   // when current flows from p to n.
end Resistor;
```

A descriptive text string enclosed in " " can be associated with a component like R. A comment which is completely ignored can be entered after //. Everything until the end of the line is then ignored. Larger comments can be enclosed in /* */.

A simple circuit with series connections of two resistors would then be described as:

```
model FirstCircuit
  Resistor R1(R=100), R2(R=200);

equation
  R1.n = R2.p;
end FirstCircuit;
```

The equation R1.n = R2.p represents the connection of pin n of R1 to pin p of R2. The semantics of this equation on structured components is the same as

```
R1.n.v = R2.p.v
R1.n.i = R2.p.i
```

This describes the series connection correctly because only two components were connected. Some mechanism is needed to handle Kirchhoff's current law, i.e. that the currents of all wires connected at a node are summed to zero. Similar laws apply to flows in a piping network and to forces and torques in mechanical systems. The default rule is that connected variables are set equal. Such variables are called *across* variables. Real variables that should be summed to zero are declared with prefix **flow**. Such variables are also called *through* variables. In Modelica we assume that such variables are positive when the flow (or corresponding vector) is into the component.

```
connector Pin
  Real v;
  flow Real i;
end Pin;
```

It is useful to introduce *units* in order to enhance the possibility to generate diagnostics based on redundant information. Modelica allows deriving new classes with certain modified attributes. The keyword **type** is used to define a new class, which is derived from the built-in data types or defined records. Defining Voltage and Current as modifications of Real with other attributes and a corresponding Pin can thus be made as follows:

```
type Voltage = Real(unit="V");
type Current = Real(unit="A");
```

```
connector Pin
  Voltage v;
  flow Current i;
end Pin;

model Resistor
  Pin p, n;     // "Positive" and "negative" pins.
  parameter Real R(unit="Ohm")  "Resistance";

equation
    R*p.i = p.v - n.v;
    p.i + n.i = 0;     // Positive currents into component.
end Resistor;
```

We are now able to correctly connect three components at one node.

```
model SimpleCircuit
  Resistor R1(R=100), R2(R=200), R3(R=300);

equation
  connect(R1.p, R2.p);
  connect(R1.p, R3.p);
end SimpleCircuit;
```

connect is a special operator that generates equations taking into account what kind of variables that are involved. The equations are in this case equivalent to

```
R1.p.v = R2.p.v;
R1.p.v = R3.p.v;
R1.p.i + R2.p.i + R3.p.i = 0;
```

In certain cases, a model library might be built on the assumption that only one connection can be made to each connector. There is a built-in function **`cardinality`**(c) that returns the number of connections that has been made to a connector c. It is also possible to get information about the direction of a connection by using the built-in function **`direction`**(c) (provided cardinality(c) == 1). For a connection, connect(c1, c2), direction(c1) returns -1 and direction(c2) returns 1. An example of the use of cardinality and direction is the bond graph components in the standard Modelica library (Appendix C).

4.4 Partial Models and Inheritance

A very important feature in order to build reusable descriptions is to define and reuse *partial models*. Since there are other electrical components with two pins like capacitor and inductor we can define a TwoPin as a base for all of these models.

```
partial model TwoPin
  Pin p, n;
  Voltage v  "Voltage drop";

equation
  v = p.v - n.v;
  p.i + n.i = 0;
end TwoPin;
```

Such a partial model can be extended or reused to build a complete model like an inductor.

```
model Inductor "Ideal electrical inductance"
  extends TwoPin;
  parameter Real L(unit="H") "Inductance";
```

```
equation
  L*der(i) = v;
end Inductor;
```

The facility is similar to inheritance in other languages. Multiple inheritance, i.e., several **extends** statements, is supported.

The type system of Modelica is greatly influenced by type theory (Abadi and Cardelli 1996), in particular their notion of subtyping. Abadi and Cardelli separate the notion of subclassing (the mechanism for inheritance) from the notion of subtyping (the structural relationship that determines type compatibility). The main benefit is added flexibility in the composition of types, while still maintaining a rigorous type system.

Inheritance is not used for classification and type checking in Modelica. An **extends** clause can be used for creating a subtype relationship by inheriting all components of the base class, but it is not the only means to create it. Instead, a class A is defined to be a *subtype* of class B, if class A contains all the public components of B. In other words, B contains a *subset* of the components declared in A. This subtype relationship is especially used for class parameterization as explained in the next section.

Assume, for example, that a more detailed resistor model is needed, describing the temperature dependency of the resistance:

```
model TempResistor "Temperature dependent electrical resistor"
  extends TwoPin;
  parameter Real R   (unit="Ohm")      "Resistance for ref. Temp.";
  parameter Real RT  (unit="Ohm/degC") "Temp. dep. Resistance.";
  parameter Real Tref(unit="degC")     "Reference temperature.";
equation
    v = i*(R + RT*(T-Tref));
end TempResistor;
```

It is not possible to extend this model from the ideal resistor model `Resistor` discussed in Chapter 2, because the equation of the `Resistor` class needs to be replaced by a new equation. Still, the `TempResistor` is a subtype of `Resistor` because it contains all the public components of `Resistor`.

4.5 Class Parameterization

We will now discuss a more powerful parameterization, not only involving values like time constants and matrices but also classes. (This section might be skipped during the first reading.) Assume that we have the description (of an incomplete circuit) as above.

```
model SimpleCircuit
  Resistor R1(R=100), R2(R=200), R3(R=300);

equation
  connect(R1.p, R2.p);
  connect(R1.p, R3.p);
end SimpleCircuit;
```

Assume we would like to utilize the parameter values given for R1.R and R2.R and the circuit topology, but exchange Resistor with the temperature dependent resistor model, TempResistor, discussed above. This can be accomplished by redeclaring R1 and R2 as follows.

```
model RefinedSimpleCircuit = SimpleCircuit(
```

```
  redeclare TempResistor R1,
  redeclare TempResistor R2);
```

Since TempResistor is a *subtype* of Resistor, it is possible to replace the ideal resistor model. Values of the additional parameters of TempResistor can be added in the redeclaration:

```
redeclare TempResistor R1(RT=0.1, Tref=20);
```

This is a very strong modification of the circuit model and there is the issue of possible invalidation of the model. We thus think such modifications should be clearly marked by the keyword **redeclare**. Furthermore, we think the modeller of the SimpleCircuit should be able to state that such modifications are not allowed by declaring a component as **final**.

```
final Resistor R3(R=300);
```

It should also be possible to state that a parameter is frozen to a certain value, i.e., is not a parameter anymore:

```
Resistor R3(final R=300);
```

To use another resistor model in the model SimpleCircuit, we needed to know that there were two replaceable resistors and we needed to know their names. To avoid this problem and prepare for replacement of a set of models, one can define a *replaceable class*, ResistorModel. The actual class that will later be used for R1 and R2 must have Pins p and n and a parameter R in order to be compatible with how R1 and R2 are used within SimpleCircuit2. The replaceable model ResistorModel is declared to be a Resistor model. This means that it will be enforced that the actual class will be a subtype of Resistor, i.e., have compatible connectors and parameters. Default for ResistorModel, i.e., when no actual redeclaration is made, is in this case Resistor. Note, that R1 and R2 are in this case of class ResistorModel.

```
model SimpleCircuit2
  replaceable model ResistorModel = Resistor;

protected
  ResistorModel R1(R=100), R2(R=200);
  final Resistor R3(final R=300);

equation
  connect(R1.p, R2.p);
  connect(R1.p, R3.p);
end SimpleCircuit2;
```

Binding an actual model TempResistor to the replaceable model ResistorModel is done as follows.

```
model RefinedSimpleCircuit2 =
  SimpleCircuit2(redeclare model ResistorModel = TempResistor);
```

Another case where redeclarations are needed is extensions of interfaces. Assume we have a definition for a Tank in a model library:

```
connector Stream
  Real pressure;
  flow Real volumeFlowRate;
end Stream;

model Tank
  parameter Area=1;
```

```
    replaceable connector TankStream = Stream;
    TankStream Inlet, Outlet;
    Real level;

  equation
    // Mass balance.
    Area*der(level) = Inlet.volumeFlowRate + Outlet.volumeFlowRate;
    Outlet.pressure = Inlet.pressure;
  end Tank;
```

We would like to extend the Tank to model the temperature of the stream. This involves both extension to interfaces and to model equations.

```
  connector HeatStream
    extends Stream;
    Real temp;
  end HeatStream;

  model HeatTank
    extends Tank(redeclare connector TankStream = HeatStream);
    Real temp;

  equation
    // Energy balance.
    Area*Level*der(temp) = Inlet.volumeFlowRate*Inlet.temp +
      Outlet.volumeFlowRate*Outlet.temp;
    Outlet.temp = temp;  // Perfect mixing assumed.
  end HeatTank;
```

The definition of HeatTank above is equivalent to the following definition (which has been automatically produced by a Modelica translator).

```
  model HeatTankT
    parameter Area=1;

    connector TankStream
      Real pressure;
      flow Real volumeFlowRate;
      Real temp;
    end TankStream;

    TankStream Inlet, Outlet;
    Real level;
    Real temp;
  equation
    Area*der(level) = Inlet.volumeFlowRate + Outlet.volumeFlowRate;
    Outlet.pressure = Inlet.pressure;
    Area*level*der(temp) = Inlet.volumeFlowRate*Inlet.temp +
      Outlet.volumeFlowRate*Outlet.temp;
    Outlet.temp = temp;
  end HeatTankT;
```

Replaceable classes are also very convenient to separate fluid properties from the actual device where the fluid is flowing, such as a pump.

4.6 Matrices

A matrix variable can be declared by appending dimensions after a component name.

```
  Real S[3, 3];
```

It is also possible to make a matrix type

```
type Transformation = Real[3, 3];
Transformation S;
```

The following definitions are appropriate for modeling 3D motion of mechanical systems.

```
type Position = Real(unit="m");
type Position3 = Position[3];

type Force = Real(unit="N");
type Force3 = Force[3];

type Torque = Real(unit="N.m");
type Torque3 = Torque[3];
```

It is now possible to introduce the variables that are interacting between rigidly connected bodies in a free-body diagram.

```
connector MbsCut
  Transformation S  "Rotation matrix describing frame A"
                    " with respect to the inertial frame";
  Position3      r0 "Vector from the origin of the inertial"
                    " frame to the origin of frame A";
  flow Force3    f  "Resultant cut-force acting at the origin"
                    " of frame A";
  flow Torque3   t  "Resultant cut-torque with respect to the"
                    " origin of frame A";
  // Velocities and accelerations omitted.
end MbsCut;
```

Such a definition can be used to model a rigid bar as follows.

```
model Bar "Massless bar with two mechanical cuts."
  MbsCut a b;
  parameter
    Position3 r[3] = [0, 0, 0]
    "Position vector from the origin of cut-frame A"
    " to the origin of cut-frame B";

equation
  // Kinematic relationships of cut-frame A and B
  b.S   = a.S;
  b.r0  = a.r0 + a.S*r;

  // Relations between the forces and torques acting at
  //   cut-frame A and B
  0 = a.f + b.f;
  0 = a.t + b.t - cross(r, a.f);
  // The function cross defines the cross product
  //   of two vectors
end Bar;
```

Matrix expressions are formed in a similar way as in MATLAB. The operators +, -, * and / can operate on either scalars, vectors or two-dimensional matrices of type real, integer or Boolean. Division is only possible with a scalar. A row vector expression or matrix of columns is formed as [$expr_1$, $expr_2$, ... $expr_n$]. A column vector or matrix of rows is formed as [$expr_1$; $expr_2$; ...

$expr_n$], i.e. with semicolon as separator between rows. Submatrices can be formed by utilizing : notation for index ranges, A[i1:i2, j1:j2]. The then and else branches of if-then-else expressions may contain matrix expressions provided the dimensions are the same. There are several built-in matrix functions like zeros, ones, identity, transpose, skew (skew operator for 3 x 3 matrices) and cross (cross product for 3-dimensional vectors). The function linspace(i1, i2, n) returns a row vector [i1, i1 + (i2-i1)/(n-1), ..., i2], i.e., n linearly spaced values in the range i1 to i2.

Matrix sizes and indices in equations must be constant during simulation. If they depend on parameters, it is a matter of "quality of implementation" of the translator whether such parameters can be changed at simulation time or only at compilation time.

Block Diagrams

We will now illustrate how the class concept can be used to model block diagrams as a special case. It is possible to postulate the data flow directions by using the prefixes **input** and **output** in declarations. This also allows checking that only one connection is made to an input, that outputs are not connected to outputs and that inputs are not connected to inputs on the same hierarchical level.

A matrix can be declared without specific dimensions by replacing the dimension with a colon: A[:, :]. The actual dimensions can be retrieved by the standard function **size**. A general state space model is an input-output **block** (restricted class, only inputs and outputs) and can be described as

```
block StateSpace
  parameter Real A[:, :],
                 B[size(A, 1), :],
                 C[:, size(A, 2)],
                 D[size(C, 1), size(B, 2)]=0;
  input     Real u[size(B, 2)];
  output    Real y[size(C, 1)];
protected
  Real   x[size(A, 2)];

equation
  assert(size(A, 1) == size(A, 2), "Matrix A must be square.");
  der(x) = A*x + B*u;
  y      = C*x + D*u;
end StateSpace;
```

Assert is a predefined function for giving error messages taking a Boolean condition and a string as arguments. The actual dimensions of A, B and C are implicitly given by the actual matrix parameters. D defaults to a zero matrix:

```
block TestStateSpace
  StateSpace S(A = [0.12, 2;  3, 1.5], B = [2, 7;  3, 1], C = [0.1,

equation
  S.u = [time; sin(time)];
end TestStateSpace;
```

The **block** class is introduced to allow better diagnostics for pure input/output model components. In such a case the correctness of the component can be analyzed locally which is not possible for components where the causality of the public variables is unknown.

4.7 Repetition, Algorithms and Functions

Regular Equation Structures

Matrix equations are in many cases convenient and compact notations. There are, however, cases when indexed expressions are easier to understand. A loop construct, **for,** which allow indexed expressions will be introduced below.

Consider evaluation of a polynomial function

$$y = \sum_{i=0}^{n} c_i x^i$$

with a given set of coefficients c_i in a vector a[n+1] with a[i] = c_{i-1}. Such a sum can be expressed in matrix form as a scalar product of the form

```
transpose(a) * [1; x; x^2; ... x^n]
```

if we could form the vector of increasing powers of x. A recursive formulation is possible.

```
xpowers[1] = 1;
xpowers[2:n+1] = xpowers[1:n]*x;
y = transpose(a) * xpowers;
```

The recursive formulation would be expanded to

```
xpowers[1] = 1;
xpowers[2] = xpowers[1]*x;
xpowers[3] = xpowers[2]*x;
...
xpowers[n+1] = xpowers[n]*x;
y = transpose(a) * xpowers;
```

The recursive formulation above is not so understandable though. One possibility would be to introduce a special matrix operator for element exponentiation as in MATLAB (.^). The readability does not increase much though.

Matrix equations like

```
xpowers[2:n+1] = xpowers[1:n]*x;
```

can be expressed in a form that is more familiar to programmers by using a for loop:

```
for i in 1:n loop
  xpowers[i+1] = xpowers[i]*x;
end for;
```

This for-loop is equivalent to n equations. It is also possible to use a block for the polynomial evaluation:

```
block PolynomialEvaluator
  parameter Real a[:];
  input  Real x;
  output Real y;

protected
  constant n = size(a, 1)-1;
```

```
    Real xpowers[n+1];

  equation
    xpowers[1] = 1;
    for i in 1:n loop
      xpowers[i+1] = xpowers[i]*x;
    end for;
    y = transpose(a) * xpowers;
  end PolynomialEvaluator;
```

The block can be used as follows:

```
    PolynomialEvaluator polyeval(a=[1, 2, 3, 4]);
    Real p;
  equation
    polyeval.x = time;
    p = polyeval.y;
```

It is also possible to bind the inputs and outputs in the parameter list of the invocation.

```
  PolynomialEvaluator polyeval(a=[1, 2, 3, 4], x=time, y=p);
```

Regular Model Structures

The **for** construct is also essential in order to make regular connection structures for component arrays, for example:

```
  Component components[n];
  equation
  for i in 1:n-1 loop
    connect(components[i].Outlet, components[i+1].Inlet);
  end for;
```

Algorithms

The basic describing mechanism of Modelica are *equations* and not assignment statements. This gives the needed flexibility, e.g., that a component description can be used with different causalities depending on how the component is connected. Still, in some situations it is more convenient to use assignment statements. For example, it might be more natural to define a digital controller with ordered assignment statements since the actual controller will be implemented in such a way.

It is possible to call external functions written in other programming languages from Modelica and to use all the power of these programming languages. This can be quite dangerous because many difficult-to-detect errors are possible which may lead to simulation failures. Therefore, this should only be done by the simulation specialist if tested legacy code is used or if a Modelica implementation is not feasible. In most cases, it is better to use a Modelica **algorithm** which is designed to be much more secure than calling external functions.

The vector `xvec` in the polynomial evaluator above had to be introduced in order that the number of unknowns are the same as the number of equations. Such a recursive calculation scheme is often more convenient to express as an algorithm, i.e., a sequence of assignment statements, if-statements and loops, which allows multiple assignments:

```
  algorithm
    y := 0;
    xpower := 1;
```

```
for i in 1:n+1 loop
  y := y + a[i]*xpower;
  xpower := xpower*x;
end for;
```

A Modelica algorithm is a function in the *mathematical sense*, i.e. without internal memory and side-effects. That is, whenever such an algorithm is used with the same inputs, the result will be exactly the same. If a function is called during *continuous* integration this is an absolute prerequisite. Otherwise the mathematical assumptions on which the integration algorithms are based on would be violated. An internal memory in an algorithm would lead to a model giving different results when using different integrators. With this restriction it is also possible to symbolically form the Jacobian by means of automatic differentiation. This requirement is also present for functions called only at **event** instants (see below). Otherwise, it would not be possible to restart a simulation at any desired time instant, because the simulation environment does not know the actual value of the internal algorithm memory.

In the **algorithm** section, ordered assignment statements are present. To distinguish from equations in the **equation** sections, a special operator, :=, is used in assignments (i.e. given causality) in the **algorithm** section. Several assignments to the same variable can be performed. Besides assignment statements, an algorithm may contain if-then-else expressions, if-then-else constructs (see below) and loops using the same syntax as in an equation-section.

Outputs, i.e., variables that appear on the left hand side of the equal sign, which are conditionally assigned, are *initialized* to their start value *whenever the algorithm is invoked.* Due to this feature it is impossible for a function to have a memory. Furthermore, it is guaranteed that the output variables always have a well-defined value.

Within an equation section of a class, algorithms are treated as expressions (one output) or as equations (several outputs). Especially, algorithms are sorted together with all other equations. For the sorting process, the calling of a function with *n* output arguments is treated as *n* implicit equations, where **every** equation depends on all output and on all input arguments. This ensures that the implicit equations remain together during sorting (and can be replaced by the algorithm invocation afterwards), because the implicit equations of the function form one algebraic loop.

In addition to the for loop, there is a while loop which is mostly used within algorithms:

```
while condition loop
  { equation }
end while;
```

Functions

The polynomial evaluator above is a special input-output block since it does not have any states. Since it does not have any memory, it would be possible to invoke the polynomial function as a function, i.e. memory for variables are allocated temporarily while the algorithm of the function is executing. Modelica allows a specialization of a class called *function* which has only public inputs and outputs, one algorithm and no equations.

The polynomial evaluation can thus be described as:

```
function PolynomialEvaluator2
  input  Real a[:];
  input  Real x;
  output Real y;

protected
```

```
    Real   xpower;
  algorithm
    y := 0;
    xpower := 1;
    for i in 1:size(a, 1) loop
      y := y + a[i]*xpower;
      xpower := xpower*x;
    end for;
  end PolynomialEvaluator2;
```

A function declaration is similar to a class declaration but starts with the **function** keyword. The input arguments are marked with the keyword **input** (since the causality is input). The result argument of the function is marked with the keyword **output**.

No internal states are allowed, i.e., the der- and new- operators are not allowed. Any class can be used as an input and output argument. All public, non-constant variables of a class in the output argument are the outputs of a function.

Instead of creating a polyeval object as was needed for the block PolynomialEvaluator:

```
PolynomialEvaluator polyeval(a=[1, 2, 3, 4], x=time, y=p);
```

it is possible to invoke the function as usual in an expression.

```
p = PolynomialEvaluator2(a=[1, 2, 3, 4], x=time);
```

It is also possible to invoke the function with positional association of the actual arguments:

```
p = PolynomialEvaluator2([1, 2, 3, 4], time);
```

Similar to Java, Modelica functions can have only **one** output argument. This is not a severe restriction, because a record can be returned in which the desired output arguments are collected together. Since the appropriate style of a Modelica function call with multiple arguments is not yet fully clear - use a functional style as Matlab or Mathematica do it, or use a procedural style, as C, C++ and Fortran do it - it is not supported in the current version of Modelica.

External functions

It is possible to call functions defined outside of the Modelica language. The body of an external function is marked with the keyword **`external`**:

```
function log
  input Real x;
  output Real y;
external
end log;
```

There is a "natural" mapping from Modelica to the target language and its standard libraries. The C language is used as the least common denominator.

The arguments of the external function are taken from the Modelica declaration. If there is a scalar output, it is used as the return type of the external function; otherwise the results are returned through extra function parameters. Arrays of simple types are mapped to an argument of the simple type, followed by the array dimensions. Storage for arrays as return values is allocated by the calling routine, so the dimensions of the returned array is fixed. More details are discussed in the appendix.

4.8 Hybrid Models

Discontinuous Models

If-then-else expressions allow modeling of a phenomena with different expressions in different operating regions. A limiter can thus be written as

```
y = if      u > HighLimit then HighLimit
    else if u < LowLimit  then LowLimit else u;
```

This construct might introduce discontinuities. If this is the case, appropriate information about the crossing points should be provided to the integrator. The use of crossing functions is described later.

More drastic changes to the model might require replacing one set of equations with another depending on some condition. It can be described as follows using matrix expressions:

```
0 = if cond_A then
  [ expression_A1l - expression_A1r;
    expression_A2l - expression_A2r ]
else if cond_B then
  [ expression_B1l - expression_B1r;
    expression_B2l - expression_B2r ]
else
  [ expression_C1l - expression_C1r;
    expression_C2l - expression_C2r ];
```

The size of the vectors must be the same in all branches, i.e., there must be *equal number of expressions (equations)* for all conditions.

It should be noted that the order of the equations in the different branches is important. In certain cases systems of simultaneous equations will be obtained which might not be present if the ordering of the equations in one branch of the if-construct is changed. In any case, the model remains valid. Only the efficiency might be unnecessarily reduced.

Conditional Models

It is useful to be able to have models of different complexities. We will now introduce *conditional equations* to support this and easy change of behavior descriptions by just setting a parameter.

Consider the case when a control system switches between two different controllers, depending on the situation. It can be described by two complementing conditional equations:

```
block Controller
  parameter Real k1, k2, k3, k4;
  parameter Boolean simple=true;
  input  Real e;
  output Real y;
protected
  Real    y1, y2, x;
equation
  if simple then
    y1 = k1*e;
  else
    der(x) = k2*e;
```

```
    y2     = k3*x + k4*e;
  end if;

  y = if simple then y1 else y2;
end Controller;
```

The condition of the if branches may only depend on constants and parameters declared final, i.e., possible to evaluate at compile time. This allows models of different complexity to be contained in one class, such that it is easy to switch between these models by just changing the value of a parameter. In the present Modelica definition conditional equations cannot contain *dynamic conditions* because it is not yet clear in which way a translator can handle such systems automatically in an efficient way.

For more complex models, *conditional components* are needed as shown in the next example where the two controllers are modeled itself as subcomponents:

```
block Controller
  input  Boolean simple=true;
  input  Real e;
  output Real y;
protected
  Controller1 c1(u=e, enable=simple);
  Controller2 c2(u=e, enable=not simple);
equation
  y = if simple then c1.y else c2.y;
end Controller;
```

Attribute `enable` is built-in Boolean input of every block with default equation "enable=true". It allows enabling or disabling a component. The enable-condition may be time and state dependent. If enable=false for an instance, its equations are not evaluated, all declared variables are held constant and all subcomponents are disabled. Special consideration is needed when enabling a subcomponent. The reset attribute makes it possible to reset all variables to their Start-values before enabling. The reset attribute is propagated to all subcomponents. The previous controller example could then be generalized as follows, taking into account that the Boolean variable simple could vary during a simulation.

```
block Controller
  input  Boolean simple=true;
  input  Real e
  output Real y
protected
  Controller1 c1(u=e, enable=simple, reset=true);
  Controller2 c2(u=e, enable=not simple, reset=true);
equation
  y = if simple then c1.y else c2.y;
end Controller;
```

Discrete Event and Discrete Time Models

The actions to be performed at events are specified by a when-statement.

```
when condition do
  assignments
end when;
```

The assignments are executed when the condition *becomes* true. It is possible to use a vector of conditions. In such a case the assignments are executed whenever *any* of the conditions becomes true.

Special actions can be performed when the simulation starts and when it finishes by testing the built-in predicates **initial**() and **terminal**( ). A special operator **new**( ) can be used to assign new values to the continuous states of a model at an event.

Let's consider discrete time systems or sampled data systems. They are characterized by the ability to periodically sample continuous input variables, calculate new outputs influencing the continuous parts of the model and update discrete state variables. The output variables keep their values between the samplings. We need to be able to activate equations once every sampling. Assume there is a built-in function **sample**(Start, Interval) that is true when time=Start + n*Interval, n>=0. A discrete first order state space model could then be written as

```
block DiscreteStateSpace
  parameter Real a, b, c, d;
  parameter Real Period=1;
  input  Real u;
  output Real y;
protected
  Real x;

equation
  when sample(0, Period) do
    new(x) := a*x + b*u;
    y      := c*x + d*u;
  end when;
end DiscreteStateSpace;
```

Note, that the special notation, **new**(x), is used to denote the value of the state variable x after the sampling.

In this case, the first sampling is performed when simulation starts. With Start > 0, there would not have been any equation defining new(x) and y initially. All variables being defined by conditional equations hold their values between the activation of the equations and have the value of their Start-attribute before the first sampling, i.e., they are discrete state variables.

For non-periodic sampling a somewhat more complex method for specifying the samplings would be used. The sequence of sampling instants could be calculated by the model itself and kept in a discrete state variable, say NextSampling. We would then like to activate a set of equations once *when* the condition **time**>= NextSampling *becomes* true. An alternative formulation of the above discrete system would thus be.

```
block DiscreteStateSpace
  parameter Real a, b, c, d;
  parameter Real Period=1;
  input  Real u;
  output Real y;
protected
  Real x, NextSampling(Start=0);

equation
  when time >= NextSampling do
    new(x) := a*x + b*u;
    y      := c*x + d*u;
    new(NextSampling) := time + Period;
  end when;
end DiscreteStateSpace;
```

Translator pragmas for efficient simulation

If the conditions used in if-the-else expressions contain relations with dynamic variables, the corresponding derivative function f might not be continuous and have as many continuous partial derivatives as required by the integration routine in order for efficient simulation. If the resulting if-then-else expression is not smooth, the modeller should have the possibility to give this extra information to the integrator. Modern integrators have indicator functions for such discontinuous events. For a relation like v1 > v2, a proper indicator function is v1 - v2. One way of giving a hint to the simulation software of possible discontinuities is to embed each such relation in a function **event** as follows.

```
y = if     event(u > HighLimit) then HighLimit
    elseif event(u < LowLimit)  then LowLimit else u;
```

One might argue that such event handling should always be used for relations. This would, however, slow down simulation in certain cases because events would be generated even if the relations would be used as boundaries for piecing together functions smoothly.

For conditional equations and Boolean equations (see below), the situation is somewhat different since more drastic changes in the model might occur, such as changing number of state variables. It thus seems appropriate that events are always generated. However, in some cases the event does not need to be triggered exactly when the condition becomes true. It might be sufficient to wait until the next step of the integration has been completed. Such events are sometimes called step events. An appropriate translator pragma for that would be to use a function **switch**(relation).

Synchronization and event propagation

Propagation of events can be done by the use of Boolean variables. A Boolean equation like

```
Out.Overflowing = Height > MaxLevel;
```

in a level sensor might define a Boolean variable, Overflowing, in an interface. Other components, like a pump controller might react on this by testing Overflowing in their corresponding interfaces

```
Pumping = In.Overflowing or StartPumping;
DeltaPressure = if Pumping then DP else 0;
```

A connection like

```
connect(LevelSensor.Out, PumpController.In);
```

would generate an equation for the Boolean component StartPump

```
LevelSensor.Out.StartPump = PumpController.In.StartPump;
```

For simulation, this equations needs to be solved for PumpController.In.StartPump. Boolean equations always needs to have a variable in either the left hand part or the right hand part or in both in order to be solvable.

An event (a relation becoming true or false) might involve the change of continuous variables. Such continuous variables might be used in some other relation, etc. Propagation of events thus might require evaluation of both continuous equations and conditional equations.

Iteration of discrete states at events

Consider the following ideal model of a diode

```
0 = if u > 0 or i > 0 then u else i;
```

To understand this model, first consider the case when i > 0, i.e. the diode is conducting. The voltage over the diode is then zero according to the equation in the first branch. When the current decreases just below zero, an event occurs due to the condition i>0, the diode opens and the second equation branch is selected, i=0. Typically the voltage is negative for a while. When u becomes a little positive again, an event occurs due to the condition u>0. If such a diode model is used in, for example, a rectifier circuit, typically a nonlinear system of equations occur involving u and i of the diode and some other variables. Since u and i occur in Boolean relations, the nonlinearities are not smooth, i.e., solving the nonlinear system of equations by means of Newton-Raphson technique is not appropriate. Between the opening and closing of the diode, the condition u > 0 **or** i > 0 is constant though. The solution procedure could take this into account, if the modeller would introduce a Boolean state variable which only changes at the events.

```
0 = if Closed then u else i;
new(Closed) = u > 0 or i > 0;
```

The last equation will not longer belong to the system of simultaneous equations due to the use of the **new**-operator, i.e., the nonlinearity has been removed. After an event, when **new**(Closed) has changed, the equations are recalculated to ensure that the new values are consistent. This recalculation is performed until no Boolean or integer variables change, i.e. this is a fix point iteration over Boolean and integers for finding the solution to a system of equations that might involve Boolean, integer and real variables.

During simulation at least u>0 would always be checked and the exact time for the crossing would be determined even if the condition would already be true due to i>0. Checking condition i>0 might be skipped when u>0 (short circuit evaluation of **or**). The model can be simulated more efficiently by rewriting the last equation as

```
new(Closed) = if Closed then i > 0 else u > 0;
```

The reason is that only one of the crossings i>0 or u>0 needs to be checked at each step depending on the condition Closed.

This style of modeling, introducing mode state variables, has shown to give efficient simulations of ideal diodes, thyristors, friction, etc. Even if there is a certain amount of rewriting of equations, or rather a certain way of thinking, when modeling, it is essential that Modelica supports this style in order to get efficient simulation.

Conditional Equations with Causality Changes

The following example models a breaking pendulum - a simple variable structure model. The number of degrees-of-freedom increases from one to two when the pendulum breaks. The example shows the needs to transfer information from one set of state variables (phi, phid) to another (pos, vel) at an event. Consider the following description with a parameter Broken.

```
model BreakingPendulum
  parameter Real m=1, g=9.81, L=0.5;

  parameter Boolean Broken;
  input Real    u;
  Real pos[2], vel[2];
  constant Real PI=3.141592653589793;
```

```
  Real phi(start=PI/4), phid;

equation
   vel = der(pos);

   if not Broken then
    // Equations of pendulum
    pos  = [L*sin(phi); -L*cos(phi)];
    phid = der(phi);
    m*L*L*der(phid) + m*g*L*sin(phi) = u;

  else;
    // Equations of free flying mass
    m*der(vel) = m*[0; -g];
  end if;
end BreakingPendulum;
```

This problem is non-trivial to simulate if Broken would be a dynamic variable because the defining equations of the absolute position "pos" and of the absolute velocity "vel" of the mass change causality when the pendulum breaks. When "Broken=false", the position and the velocity are calculated from the Pendulum angle "phi" and Pendulum angular velocity "phid". After the Pendulum is broken, the position and velocity are state variables and therefore known quantities in the model.

As already mentioned, conditional equations with dynamic conditions are presently not supported because it is not yet clear in which way a translator can handle such a system automatically. It might be that a translator pragma is needed to guide the translation process. It is possible to simulate variable causality systems, such as the breaking pendulum, by reformulating the problem into a form where no causality change takes place using conditional block models:

```
record PendulumData
   parameter Real m, g, L;
end PendulumData;


partial model BasePendulum
   PendulumData p;
   input   Real u;
   output  Real pos[2], vel[2];
end BasePendulum;


block Pendulum
   extends BasePendulum;
   constant Real PI=3.141592653589793;
   output   Real phi(start=PI/4), phid;
equation
   phid = der(phi);
   p.m*p.L*p.L*der(phid) + p.m*p.g*p.L*sin(phi) = u;

   pos = [p.L*sin(phi); -p.L*cos(phi)];
   vel = der(pos);
end Pendulum;


block BrokenPendulum
   extends BasePendulum;
equation
   vel = der(pos);
   p.m*der(vel) = p.m*[0; -p.g];
```

```
end BrokenPendulum;


model BreakingPendulum2
   extends BasePendulum(p.m=1, p.g=9.81, p.L=0.5);
   input Boolean Broken;
protected
   Pendulum       (p=p, u=u, enable=not Broken);
   BrokenPendulum (p=p, u=u, enable=Broken);
equation
   when Broken do
      new(BrokenPendulum.pos) = Pendulum.pos;
      new(BrokenPendulum.vel) = Pendulum.vel;
   end when
algorithm
   if not Broken then
      pos := Pendulum.pos;
      vel := Pendulum.vel;
   else
      pos := BrokenPendulum.pos;
      vel := BrokenPendulum.vel;
   end if
end BreakingPendulum2;
```

This rewriting scheme is always possible and results in a larger model. It has the drawback that the same physical variable is represented by several model variables. In some cases, such as for the breaking pendulum, it is possible to avoid this drawback:

```
model BreakingPendulum3
  parameter Real m=1, g=9.81;

  input Boolean Broken;
  input Real    u;
  Real pos[2], vel[2];
  constant Real PI=3.141592653589793;
  Real phi(start=PI/4), phid;
  Real L=0.5, Ldot;

equation
  pos = [L*sin(phi); -L*cos(phi)];
  vel = der(pos);
  phid = der(phi);
  Ldot = der(L);

  0 = if not Broken then [
    // Equations of pendulum
    m*der(phid) + m*g*L*sin(phi) - u;
    der(Ldot)]
  else
    // Equations of free flying mass
    m*der(vel) = m*[0; -g];
end BreakingPendulum3;
```

The trick was to use complete polar coordinates including the length, L and to give a differential equation for L in the non Broken mode. If the derivatives of some variables are not calculated during the "not Broken"-phase, the variables "pos" and "vel" can be considered as algebraic variables. A simulator thus has the possibility to remove them from the set of active state variables.

4.9 Units and Quantities

The built-in "Real" type of Modelica has additional attributes to define *unit* properties of variables:

```
type Real
  parameter StringType quantity    = "";
  parameter StringType unit        = "" "unit in equations";
  parameter StringType displayUnit = "" "default display unit";
  ...
end Real;

// define quantity types
type Force = Real(final quantity="Force", final unit="N");
type Angle = Real(final quantity="Angle", final unit="rad",
                         displayUnit="deg");

// use the quantity types
Force f1   , f2  (displayUnit="kp");
Angle alpha, beta(displayUnit="rad");
```

The *quantity* attribute defines the category of the variable, like Length, Mass, Pressure. The *unit* attribute defines the unit of a variable as utilized in the equations. That is, all equations in which the corresponding variable is used are only correct, provided the numeric value of the variable is given with respect to the defined unit. Finally, *displayUnit* gives the default unit to be used in tools based on Modelica for interactive input and output. If, for example, a parameter value is input via a menu, the user can select the desired unit from a list of units, using the "displayUnit" value as default. When generating Modelica code, the tool makes the conversion to the defined "unit" and stores the used unit in the "displayUnit" field. Similarly, a simulator may convert simulation results from the "unit" into the "displayUnit" unit before storing the results on file. All of these actions are optional. If tools do not support units, or a specific unit cannot be found in the unit database, the value of the "unit" attribute could be displayed in menus, plots etc.

The *quantity* attribute is used as grouping mechanism in an interactive environment: Based on the quantity name, a list of units is displayed which can be used as *displayUnit* for the underlying physical quantity. The quantity name is needed because it is in general not possible to determine just by the *unit* whether two different units belong to the same physical quantity. For example,

```
type Torque = Real(final quantity="MomentOfForce", final unit="N.m"
type Energy = Real(final quantity="Energy"       , final unit="J");
```

the units of type Torque and type Energy can be both transformed to the same *base units*, namely "kg.m2/s2". Still, the two types characterize different physical quantities and when displaying the possible displayUnits for torque types, unit "J" should not be in such a list. If only a unit name is given and no quantity name, it is not possible to get a list of displayUnits in a simulation environment.

Together with Modelica a *standard package* of *predefined* quantity and connector types is provided in the form as shown in the example above. This will give some help in standardization of the interfaces of models. Note, that the prefix **final** defines that the quantity and unit values of the predefined types cannot be modified.

Conversion between units is **not** supported within the Modelica language. This simplifies a Modelica translator considerably, especially because a unit-database with its always incomplete collection of units is not needed, see e.g. (Cardarelli 1997). As a consequence, the semantics of a correct Modelica model is independent of the unit attributes and the Modelica translator can ignore them during code generation. Especially, the unit attributes need *not* be checked for a connection, i.e., connected variables may have different quantities and units.

Much more support on units and quantities will be given by tools based on Modelica. This will be considered as "quality of implementation". An object-diagram editor may, for example, support automatic unit conversion when two interfaces are connected. As a general rule it will always be allowed to connect any variable to a variable which has no quantity and unit associated with it. Furthermore, a Modelica translator may optionally check equations on correct dimensionality (this will produce only warning messages, i.e., code will be produced anyway). The equation "f=m*a" would, for example, produce a warning, if "f" is given in "N.m" because then the units are not compatible to each other. The variables in the equations may have non-SI units.

Therefore, for example, the compiler will not detect that "f=m*a" is an error, if the units "N" for "f", "g" for "m" and "m/s^2" for "a" are used. Dimension checking is done by transforming the "quantity" information into one of the seven base "quantities" (like "Mass", "Length").

Usually, units are associated with types. There are however elements where instances may have a different unit by redefinition of the quantity type. Example:

```
type Voltage = Real(final quantity="Voltage", final unit="V");

model SineSignal
  parameter Real  freq (unit="Hz" );
  parameter Angle phi;

  replaceable type SineType = Real;
  parameter SineType Amplitude;
  output    SineType y;
  constant  Real PI=3.141592653589793;
equation
  y = Amplitude*sin(2*PI*freq*time + phi);
end SineSignal;

model Circuit
  SineSignal    sig(redeclare SineType = Voltage);
  VoltageSource Vsource;
    ...
equation
  connect(sig.y, Vsource.in);
end Circuit;
```

In a block diagram library there is a general sine signal generator. When it is used to generate a voltage sine for a voltage source, the output of the signal generator should have a unit of "V". This can be accomplished by having the type of the amplitude and of the output as a replaceable type which can be changed appropriately when this signal generator is instantiated.

4.10 Annotations for Graphics and Documentation

In addition to the mathematical model with variables and equations, additional information is needed for example to represent icons, graphical layout, connections and extended documentation. Graphically representing models as interconnected submodels displayed as icons, supports their quick understanding. As most contemporary tools provide facilities to build models graphically, Modelica has language constructs to represent icons, graphical layout and the connections between submodels.

Modelica supports property lists for the various components. Such lists can be used to store graphical, documentation and tool related annotations. Each component can have a list designated by the keyword **annotation**. The value of such annotations can be according to any class, i.e., it can be created using a class modification. The strong type checking is abandoned in this case because of the need for various modeling tools to use different kinds of annotations. Since such annotation values are normally generated and read by tools, i.e., not directly edited by humans, there is a reduced need for having redundant type information. However, in order that graphical and documentation information can be exchanged between tools, a minimum set of annotation components are specified.

Graphical representation of models

Graphical annotation information is given in three separate contexts:

- Annotations associated with a component, typically to specify position and size of the component.
- Annotations of a class to specify the graphical representation of its icon (see above), diagram, and common properties such as the local coordinate system.
- Annotations associated with connections, i.e., route, color of connection line, etc.

The example below shows the use of such graphical attributes to define a resistor.

```
model Resistor
  Pin p annotation (extent=[-110, -10; -90, 10]);
  Pin n annotation (extent=[ 110, -10;  90, 10]);

  parameter R "Resistance in [Ohm]";

equation
  R*p.i = p.v - n.v;
  n.i = p.i;

public
  annotation (Icon(
    Rectangle(extent=[-70, -30; 70, 30], style(fillPattern=1)),
    Text(extent=[-100, 55; 100, 110], string="%name=%R"),
    Line(points=[-90, 0; -70, 0]),
    Line(points=[70, 0; 90, 0])
    ));
end Resistor;
```

The resistor has two pins, and we specify two opposite corners of the extent of their graphical representation. An icon of the Resistor is defined by a rectangle, a text string and two lines. For the rectangle we specify additional style attributes for fill pattern.

The extent specified for a component is used to scale the icon image. The icon is drawn in the master coordinate system specified in the component's class. The icon is scaled and translated so the coordinate system is mapped to the region defined in the component declaration.

The attribute set to represent component positions, connections and various graphical primitives for building icons is shown below. The attribute structures are described through Modelica classes. Points and extents (two opposite points) are described in matrix notation.

```
type Point = Real[2];      // [x, y]

type Extent = Real[2,2];   // [x1, y1; x2, y2]

record CoordinateSystem    // Attribute to class
  Extent extent;
```

```
  Point grid;
  Point size;
end CoordinateSystem;

record Placement           // Attribute for component
  Extent extent;
  Real rotation;
end Placement;

record Style
  Integer color[3], fillColor[3];    // RGB
  Integer pattern, fillPattern, thickness, gradient, smooth, arrow,
  String font;
end Style;

record Route                // Attribute for connect
  Point points[:];
  Style style;
  String label;
end Route;

// Definitions for graphical elements
record Line = Route;

record Polygon = Route;

record GraphicItem
  Extent extent;
  Style style;
end GraphicItem;

record Rectangle = GraphicItem;

record Ellipse = GraphicItem;

record Text
  extends GraphicItem;
  String string;
end Text;

record BitMap
  extends GraphicItem;
  String URL;              // Name of bitmap file
end BitMap;
```

The graphical unit of the master coordinate system used when drawing lines, rectangles, text etc. is the baseline spacing of the default font used by the graphical tool, typically 12 points for a 10 point font (note: baseline spacing = space between text lines).

Documentation of models

In practical modeling studies, documenting the model is an important issue. It is not only for writing a report on the modeling work, but also to record additional information which can be consulted when the model is reused. This information need not necessarily be completely structured and standardized in the sense that Modelica language constructs are available for all aspects. The following aspects should typically be recognized:

History information

  Major milestones, like creation, important changes, release into public accessibility should be recorded. Information to store are the author, date and a brief description. This functionality is comparable with version control of software, using tools such as SCCS or RCS. If a specific modeling procedure is used, the mile stones of such a procedure can be recorded in this part.

References to literature
: References to external documents and/or scientific literature for understanding the model, its context and/or underlying theory should be mentioned here. The format can be like a literature reference list in an scientific article.

Validation information
: This concerns the reference (model or measurement data) to which the model is validated and criteria for validation. Also the simulation experiments used for the validation should be mentioned.

Explanation and sketches
: A brief text describing the model or device, a kind of 'manual page' of the model. Schematic drawings or sketches can be incorporated for better understanding.

User advice
: This extension of the explanation part, concerns additional remarks giving hints for reuse of the model.

Basic documentation functionality is available in Modelica. This consists of an annotation attribute **`Documentation`** which is further structured into key/text pairs.

```
annotation (Documentation(
  key1 = "Text string",
  key2 = "Text string"
  ));
```

Currently, no further detail on structuring information is given. The information is given as plain text in the appropriate category. It is likely that companies have their own way of documenting their models and experiments, so that different ways of filling in the documentation information are needed.

---

5. Overview of Present Languages

In this chapter an overview is given on the languages which have been used as starting point for the Modelica design, i.e., Modelica builds upon the experience gained with these languages.

Since the definition of CSSL in 1967 (Strauss, 1967), most modeling languages are essentially block oriented with inputs and outputs and the mathematical models are defined as assignment statements for auxiliary variables and derivatives. Physical equations thus need to be transformed to a form suitable for calculations. The only aid in transforming the equations to an algorithm for calculating derivatives is automatic sorting of the equations.

The languages that form the base of Modelica, all have general equations, i.e. expression = expression, as the basic element. Hierarchical decomposition and reuse are typically supported by some kind of model class. Typically, the languages have provisions to describe physical connection mechanisms, i.e. to associate a set of variables with some kind of port. Such ports can be used at higher hierarchical levels when connecting submodels without having to deal with individual variables.

ASCEND

ASCEND (Advanced System for Computation in ENgineering Design) was developed at

Carnegie Mellon University, PA, USA to be a rapid model building environment for complex models comprising large sets of nonlinear algebraic equations (Piela 1989, Piela et.al. 1991). The language is textual. It supports quantity equations, single inheritance and hierarchical decomposition, but it does not have well defined submodel interfaces. The application domain is chemical process modeling. Later versions support dynamic continuous time modeling.

Dymola

Dymola (Dynamic Modeling Language), as introduced already in 1978 (Elmqvist, 1978), is based on equations for non-causal modeling, model types for reuse and submodel invocation for hierarchical modeling. The Dymola translator utilizes graph theoretical methods for causality assignment, for sorting and for finding minimal systems of simultaneous equations. Computer algebra is used for solving for the unknowns and to make simplifications of the equations. Constructs for hybrid modeling, including instantaneous equations, was introduced in 1993 (Elmqvist et.al. 1993). Crossing functions for efficient handling of state events are automatically generated. A graphical editor is used to build icons and to make model compositions (Elmqvist et.al. 1996). Major application areas include multi-body systems, drive-trains, power electronics and thermal systems.

gPROMS

gPROMS (Barton and Pantelides 1994, Oh and Pantelides 1996) is a general process modeling system. The language is a further development of SPEEDUP. Continuous parts of the process are modelled by DAE’s. A task concept handles the discrete events. Continuous models and tasks are combined into a single entity called process. The gPROMS language has constructs for certain kinds for partial differential equations. The major application domain is chemical process modeling.

MOSES

MOSES (Modular Object-oriented Software Environment for Simulation) is a prototype system for object-oriented modeling based on the experience with Omola. It consists of a "Model Definition Language" (MDL), a "Data Model" (DM) yielding minimum mismatch with MDL, and an object-oriented data base system based on GemStone to meet the hard data management problems involved in complex system modeling. Combined continuous and discrete-time (hybrid) systems are supported. The main application area is robotics.

NMF

The Neutral Model Format (NMF) (Sahlin et.al. 1996) is a language in the Dymola and Omola tradition and was first proposed as a standard to the building and energy systems simulation community in 1989. The language is formally controlled by a committee within ASHRAE (Am. Soc. for Heating, Refrigerating and Air-Conditioning Engineers). Several independently developed NMF tools and model libraries exist, and valuable lessons on language standardization and development of reusable model libraries have been learned. Salient features of NMF are: (1) good support for model documentation, (2) dynamical vector and parameter dimensions (a model can, e.g., calculate required spatial resolution for PDE), (3) full support for calls to foreign models (e.g. legacy or binary Fortran or C models) including foreign model event signals.

ObjectMath

ObjectMath (Object Oriented Mathematical Modeling Language), (Fritzson et.al. 1995) is a high-level programming environment and modeling language designed as an extension to

Mathematica. The language integrates object-oriented constructs such as classes, and single and multiple inheritance with computer algebra features from Mathematica. Both equations and assignment statements are included, as well as functions, control structures, and symbolic operations from standard Mathematica. Other features are parameterized classes, hierarchical composition and dynamic array dimension sizes for multi-dimensional arrays. The environment provides a class browser for the combined inheritance and composition graph and supports generation of efficient code in C++ or Fortran90. The user can influence the symbolic transformation of equations or expressions by manually specifying symbolic transformation rules, which also gives an opportunity to control the quality of generated code. The main application area so far has been in mechanical systems modeling and analysis.

Omola

Omola (Andersson 1984, Mattsson et.al. 1993) is an object-oriented and equation based modeling language. Models can be decomposed hierarchically with well-defined interfaces that describe interaction. All model components are represented as classes. Inheritance and specialization support easy modification. Omola supports behavioral descriptions in terms of differential-algebraic equations (DAE), ordinary differential equations (ODE) and difference equations. The primitives for describing discrete events allow implementation of high level descriptions as Petri nets and Grafcet. An interactive environment called OmSim supports modeling and simulation: graphical model editor, consistency analysis, symbolic analysis and manipulation to simplify the problem before numerical simulation, ODE and DAE solvers and interactive plotting. Applications of Omola and OmSim include chemical process systems, power generations and power networks.

SIDOPS+

SIDOPS+ supports nonlinear multidimensional bond-graph and block-diagram models, which can contain continuous-time parts and discrete-time parts (Breunese and Broenink, 1997). The language has facilities for automated modeling support like polymorphic modeling (separation of the interface and the internal description), multiple representations (component graphs, physical concepts like bond graphs or ideal physical models and (acausal) equations or assignment statements), and support for reusability (e.g. documentation fields, physical types). Currently, SIDOPS+ is mainly used in the field of mechatronics and (neural) control. It is the model description language of the package 20-SIM (Broenink, 1997). SIDOPS+ is the third generation of SIDOPS which started as a model description language for single-dimensional bond-graph and block-diagram models.

Smile

Smile is an object-oriented and equation-based modeling and simulation environment. The object-oriented and imperative features of Smile’s model *description language* are very similar to Objective-C. Equations may either be specified symbolically or as procedures; external modules can be integrated. Smile also has a dedicated *experiment description language*. The system consists of translators for the above-mentioned languages, a simulation engine offering several numeric solvers, and components for interactive experimenting, visualization, and optimization. Smile’s main application domain traditionally has been the simulation of solar energy equipment and power plants (Tummescheit and Pitz-Paal, 1997), but thanks to its object-oriented modeling features it is applicable to other classes of complex systems as well. An extension of Smile to support Modelica is planned (Ernst, et.al., 1997).

U.L.M. - Allan

The goal of ALLAN (Pottier, 1983; Jeandel 1997) is to free engineers from computer science and numerical aspects, and to work towards capitalization and reuse of models. This means non-causal and hierarchical modeling. A graphical representation of the model is associated to the textual representation and can be enhanced by a graphical editor. A graphical interface is used for hierarchical model assembly. The discrete actions at the interrupts in continuous behavior are managed by events. Automatons (synchronous or asynchronous) are available on events. FORTRAN or C code can be incorporated in the models. Two translators toward the NEPTUNIX and ADASSL (modified DASSLRT) solvers are available. Main application domains are energy systems, car electrical circuits, geology and naval design.

The language U.L.M. has been designed in 1993 with the same features as the ALLAN language in a somewhat different implementation (Jeandel, 1996). It is a model exchange language linked to ALLAN. All aspects of modeling are covered by the textual language. There is an emphasis on the separation of the model structure and the model numerical data for reuse purposes. It also has an interesting feature on model validation capitalization.

VHDL-AMS

VHDL-AMS (IEEE, 1997) is an extension to the discrete circuit modeling language VHDL for combined continuous and discrete models. Structuring is done by means of entities and architectures. An entity defines the external view of a component including its parameters (generics), its discrete signal interface and its continuous interface (ports). The architecture associated with an entity describes the implementation which may contain equations (DAE's). VHDL-AMS is a large and rich modeling language targeted mainly at the application domain of electronics hardware. Several extensions of VHDL towards full object orientation have been proposed (see e.g. Benzakki, et.al., 1997), but the continous modeling extensions of VHDL-AMS were not yet taken into account in this work.

---

6. Design Rationale

As already pointed out in the beginning of this chapter, Modelica is an object oriented, equation-based, declarative data-oriented modeling language for non-causal modeling of physical systems. In this section we give a short rationale of the language from a computer science point of view by explaining some of the design principles and decisions behind the language in its current form.

The following are a set of general principles and design goals that have been applied more or less consistently during the design of the Modelica language. We give several examples how these goals have influenced the current design.

- Engineering tool

  The Modelica language is designed to be an engineering tool for modeling of realistic physical systems, usually with the aim of simulating, optimizing or controlling such systems. Thus, the language has to fulfill the requirements of engineering, such as allowing efficient implementation, coping with large physical systems composed of different kinds of subsystems.

- Reliability and correctness

  The language as an engineering tool should support the construction of reliable and correct software. This goal is rather fundamental to the overall design of Modelica. For example, readability of system models is important since this contributes to reliability in engineering, even at the cost of more verbose code. This is the main reason for having named parameter passing in Modelica, also present in Ada. The strong typing in Modelica has been introduced to provide partial verification of internal consistency. The declarative and functional style of Modelica helps avoid certain errors and enhances code reuse.

- Coping with system evolution

  Large software systems are always evolving, e.g. by adding new functionality, adapting to new hardware, enhancing performance, etc. Most large software systems are always in a transitional situation where most things work and a few things do not work. We say that an evolving system is reliable if it does not break too often or too extensively in spite of change. The strong type system of Modelica is one way of controlling system evolution, by partially verifying system models at each stage. The Modelica class and package concepts, integrated with the type system, provide a module mechanism to control system complexity.

- Generality, uniformity

  The design of Modelica emphasizes generality and uniformity. This makes the language easier to learn, yet powerful. Therefore the concepts of model, type, connector, block, package and function in Modelica have been designed to be just restricted versions of the general class concept. A general static and strong type system designed by Luca Cardelli (Cardelli 1988, Cardelli 1991), has been adopted for Modelica. This type system integrates object orientation with multiple inheritance, subtyping, and parametric polymorphism - the latter also known as generics in Ada and templates in C++. Another example of uniformity and generality is that named and positional parameter passing is available for both class specialization and function calls in Modelica.

- Declarativity and referential transparency

  Most high level specification languages are declarative, including Modelica, since this allows expressing properties of systems without specifying in detail how, or in what order, such properties should be realized. For example, Modelica views object orientation as a declarative structuring concept for mathematical modeling in contrast to the non- declarative view of languages like SmallTalk, which regard object orientation as message passing between (dynamically) created objects. Modelica functions are declarative and encourages a functional programming style. They are essentially side effect free mathematical functions. The body of a function is called an algorithm section. From the equation point of view, such an algorithm section can be regarded as a strongly connected set of equations.

- Adherence to common de facto language standards

  Modelica tries to be somewhat compatible with several existing common programming languages, since this makes Modelica easier to learn and to use for engineers. For example, Modelica has adopted some of the Java syntax and the UniCode character standard, and uses the Matlab notation for matrix operations.

- High level of abstraction

  Since Modelica is a specification language, it is designed to allow abstraction from unnecessary detail. The language obtains its strong abstraction power by being based on equations integrated with object oriented structuring concepts and object connection mechanisms.

- Code reuse

  Code reuse is a desirable but hard-to-reach goal for software development. Modelica contributes to this goal in several ways. Its non-causal equation-based modeling style permits model components to be reused in different contexts, automatically adapting to the data flow order in specific simulation applications, i.e. the Modelica compiler automatically arranges equations for solution with particular inputs or outputs. Object orientation and polymorphism significantly enhances the potential for reuse of Modelica model components.

- Mathematical foundation

  The Modelica language has a strong mathematical foundation in the sense that a Modelica model is expanded (from a semantic point of view) into a set of differential-algebraic equations. Thus, Modelica is primarily equation-based. Equations can be conditional, to represent discrete-event features and enable hybrid modeling.

---

7. Examples

Modelica has been used to model various kinds of systems. (Otter et.al. 1997) describes modeling of automatic gearboxes for the purpose of real-time simulation. Such models are non-trivial because of the varying structure during gear shift utilizing clutches, free wheels and brakes. (Mattsson 1997) discusses modeling of heat exchangers. Class parameters of Modelica are used for medium parameterization and regular component structures are used for discretization in space of the heat exchanger. (Tummescheit et.al. 1997) discusses thermodynamical and flow oriented models. (Broenink 1997) describes a Modelica library with bond graph models for supporting the bond graph modeling methodology.

---

8. Conclusions

The Modelica effort has been described and a definition of Modelica has been given. This report (September 1997) defines Modelica version 1.

The next phase involves design of standard function and model libraries. There is ongoing work to write books on the Modelica language and on Modelica model libraries. Several Modelica tools are also under development. There are discussions to extend the Modelica design into, for example, handling partial differential equations and discrete event models.

More information and the most actual status of the Modelica effort can be found at

```
URL: http://www.Dynasim.se/Modelica
```

---

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Appendix

Appendix A. Mathematical Description of Hybrid DAEs

In this section, the mapping of a Modelica model into an appropriate mathematical description form is discussed.

The result of the modeling process is a set of ordinary differential equations, often accompanied with algebraic constraint equations, thus forming a set of Differential and Algebraic Equations (DAE). The initial values of the state variables need to be specified, implying that the DAE is mathematically formulated as a so-called Initial Value Problem. This DAE is used for simulation or other analysis activities. DAEs may have discontinuities or the structure of a DAE may change at certain points in time. Such types of DAEs are called *hybrid DAE*s. Events are used to stop continuous integration at discontinuities of a hybrid DAE. After applying the discontinuous change, the integration is restarted. A hybrid DAE is mathematically described by a set of equations of the form

```
(1a) Residue Equations:     0 = f(dx/dt, x, y, t, m),  df/[dx/dt;y]
(1b) Monitor Functions:     z:= g(dx/dt, x, y, t, m)
(1c) Update Functions : [m,x]:= h(dx/dt, x, y, t, m, x^post)
```

Additionally, every equation is a function of the parameters **p** and of the input functions **u**(t). This dependency is not explicitly shown in (1) for clarity of the equations. The variables have the following meaning:

- t time, the independent (real) variable.
- **x**(t) (real) variables appearing differentiated.
- **y**(t) (real) algebraic variables.
- **u**(t) known (real) functions of time.
- **m** discrete variables of any type (real, integer, string, ...) defining the current **mode**.
- **p** parameters, i.e., constant variables.

The *residue equations* (1a) are used for continuous integration. During integration, the discrete variables **m** are not changed. The *monitor functions* (1b) are also evaluated during continuous integration. If one of the signals **z** crosses zero, the integration is halted and an event occurs. The special case of a time event, "z = t - te", is also included. For efficiency reasons, time events are usually treated in a special way, since the time instant of such an event is known in advance. At every event instant, the *update functions* (1c) are used to determine new values of the discrete variables and of new initial values for the states **x**. The change of discrete variables may characterize a new structure of a DAE where elements of the state vector **x** are *disabled*. In other words, the number of state variables, algebraic variables and residue equations of a DAE may change at event instants by disabling the appropriate part of the DAE. For clarity of the equations, this is not explicitly shown by an additional index in (1).

In (Mosterman and Biswas 1996) it is shown that for the update functions **h** it is necessary to distinguish the usage of **x** in equations and assignment statements from the usage in Boolean expressions, such as "**if** x > 0 **then** ...". Changes of discrete variables may cause jumps in state variables, and Boolean expressions may have to utilize the values immediately after the jump occurred. In (1) these state variables are supplied as additional function argument $\mathbf{x}^{post}$, where the index "post" stands for "posterior" value. The update functions are used in the following iteration procedure to determine new *consistent* initial conditions:

```
x^new := x
loop
   [m^new,x^new]:= h(dx/dt, x, y, t, m, x^new)
   if m^new == m then break
   repeat
      m := m^new
      [m^new,x^new]:= h(dx/dt, x, y, t, m, x^new)
   until m^new == m
   x := x^new
   solve "0 = f(dx/dt, x, y, t, m)" for dx/dt and y (x,t,m are fix
end loop
```

If, for example, several ideal Coulomb friction elements are used in a model, it is not possible to decide in advance the mode of each friction element (whether it is stuck or it slides) when the relative velocity is zero. An iteration is needed to determine the modes which are compatible with the forces and torques acting on the mechanical device. According to (Mosterman and Biswas 1996) an inner loop is needed in order not to converge to a physically wrong solution. The equations of the inner loop are always evaluated with the state vector **x** of the last consistent mode **m**. The inner loop is iterated until the next consistent mode **m** is found. The start of an integration is treated as an event instant, i.e., an iteration also takes place at the initial time. At every step of the iteration a non-linear equation has to be solved. In order that this is possible, the Jacobian of the non-linear equation needs to be regular, as it was stated in (1a).

The hybrid DAE (1) is not the most general one, but it has a clearly defined view and structure. Especially, (1a) can be transformed into state space form, at least numerically, since the Jacobian is required to be regular. Generalizations are possible in the direction of higher index DAEs where the Jacobian of (1a) is singular. This leads to additional difficulties during integration and especially for event restart because the non-linear equation cannot be solved due to the singular Jacobian. Other generalizations concern the determination of the initial configuration by allowing the specification of any variable at the initial time and by calculating the remaining ones. A third generalization may use other algorithms to determine a consistent configuration after an event occurred, e.g., by solving a complementary problem, see (Pfeiffer and Glocker 1996) for details. For a *certain class* of higher index DAE systems, algorithms are available to automatically differentiate selected equations of (1a), choose appropriate variables to be no longer states (= dummy derivative method) and transform to a DAE (1) with a regular Jacobian.

The Modelica language allows a direct and convenient specification of physical systems. *A Modelica translator maps a Modelica model into a hybrid DAE (1),* or in one of its generalizations if these are available. The mapping into (1) is straightforward by expanding all class definitions (flattening the inheritance tree) and adding the equations and assignment statements of the expanded classes for every instance of the model to (1). The resulting hybrid DAE usually contains a huge number of sparse equations. Therefore, direct simulation of a hybrid DAE (1) which was generated by a Modelica translator requires sparse matrix methods.

There are several simulation environments available, such as Allan, Dymola, gPROMS, Ida (NMF) or Omola, which preprocess (1) symbolically to arrive at a form which can be evaluated much more efficiently by numerical algorithms. Especially, efficient graph-theoretical algorithms are available to transform (1) automatically into the following form which is called **sorted** hybrid DAE:

$$
\begin{array}{lll}
\text{(2a) Residue Equations:} & 0 & = \mathbf{f}^r(d\mathbf{x}^i/dt, \mathbf{y}^i, \mathbf{x}, t, \mathbf{m}),\ d\mathbf{f}^r/[d\mathbf{x}^i/dt; \mathbf{y}^i]\ : \\
\text{(2b) Exp. dx-Functions:} & d\mathbf{x}^e/dt & := \mathbf{f}^x(d\mathbf{x}^i/dt, \mathbf{y}^i, \mathbf{x}, t, \mathbf{m}) \\
\text{(2c) Exp. y-Functions :} & \mathbf{y}^e & := \mathbf{f}^y(d\mathbf{x}^i/dt, \mathbf{y}^i, \mathbf{x}, t, \mathbf{m}) \\
\text{(2d) Monitor Functions:} & \mathbf{z} & := \mathbf{g}\ (d\mathbf{x}^i/dt, \mathbf{y}^i, \mathbf{x}, t, \mathbf{m}) \\
\text{(2e) Update Functions :} & [\mathbf{m}, \mathbf{x}] & := \mathbf{h}\ (d\mathbf{x}^i/dt, \mathbf{y}^i, \mathbf{x}, t, \mathbf{m}, \mathbf{x}^{post})
\end{array}
$$

where the vector of algebraic variables **y** is split into implicit variables $\mathbf{y}^i$ and explicitly solvable algebraic variables $\mathbf{y}^e$. The vector of state derivatives d**x**/dt is split into implicit variables $d\mathbf{x}^i/dt$ and explicitly solvable variables $d\mathbf{x}^e/dt$, respectively. When using an *implicit integrator*, only equations (2a,2b) need to be solved during continuous integration. Equations (2c) are effectively hidden from the solver. They need only be evaluated for external usage (e.g., to store output points to be plotted). At initial time and at events, only the non-linear equation (2a) has to be solved. Again the dimension of the original equations has reduced considerably. It is also possible to use *explicit integration* methods, such as Runge-Kutta algorithms. During continuous integration, the integrator provides **x** and t. The model function solves (2a) for the implicit variables, uses the result to evaluate (2b) and returns the complete vector of state derivatives d**x**/dt. This procedure is useful for *real-time* simulation where only explicit one-step methods can be used and for non-stiff systems where the number of implicit equations is small and/or linear.

To summarize, a Modelica translator maps a Modelica model into the hybrid DAE (1). By a subsequent symbolic processing, (1) can be transformed into the sorted hybrid DAE (2).

Appendix B. Formal Specification of Modelica

Appendix B.1. Modelica Syntax

The following syntactic meta symbols are used (extended BNF):

```
[ ]  optional
{ }  repeat zero or more times
```

The following lexical units are defined:

```
IDENT = // Identifiers have the same definition as in Java

STRING = // String constant as in C

UNSIGNED_NUMBER = // Decimal number notation
```

Keywords and built-in operators of the Modelica language are written in bold face. Modelica uses the same comment syntax as C++ and Java.

Model definition

```
model_definition:
   { class_definition ";" | import STRING ";" }
```

Class definition

```
class_definition :
      [ partial ]
   ( class | model | record | block | connector | type |
     package | function )
   IDENT comment
   ( composition end IDENT |
     "=" IDENT [ array_dimensions ] [ class_modification ] )

composition  :
   element_list
   { public element_list |
     protected element_list |
     equation_clause |
     algorithm_clause
   }
   [ external ]

element_list :
   { element ";" | annotation  ";" }

element :
   [ final ] ( [ replaceable ] class_definition | extends_clause |
```

```
                   component_clause )
```

Extends

```
extends_clause :
   extends name [ class_modification ]
```

Component clause

```
component_clause:
   type_prefix type_specifier component_list

type_prefix :
   [ flow ] [ parameter | constant ] [ input | output ]

type_specifier :
   name

component_list :
   component_declaration { "," component_declaration }

component_declaration :
   declaration comment

declaration :
   IDENT [ array_dimensions ] [ modification ]

array_dimensions :
   "[" subscript { "," subscript } "]"
```

Modification

```
modification :
   class_modification
 | "=" expression


class_modification :
   "(" { argument_list } ")"

argument_list :
   argument { "," argument }

argument :
   element_modification
 | element_redeclaration

element_modification :
   [ final ] component_reference modification

element_redeclaration :
   redeclare [ final ]
   ( [ replaceable ] class_definition | extends_clause | component_c

component_clause1 :
   type_prefix type_specifier component_declaration
```

Equations

```
equation_clause :
  equation { equation ";" | annotation  ";" }
```

```
algorithm_clause :
   algorithm { equation ";" | annotation  ";" }

equation :
  ( simple_expression [ ( "=" | ":=" ) expression ]
    | conditional_equation
    | for_clause
    | while_clause )
  comment

conditional_equation :
   if expression then
     { equation ";" }
   { elseif expression then
     { equation ";" }
   }
   [ else
     { equation ";" }
   ]
   end if

for_clause :
  for IDENT in expression ":" expression [ ":" expression ] loop
     { equation ";" }
  end for

while_clause :
  while expression loop
    { equation ";" }
  end while
```

Expressions

```
expression :
   simple_expression
 | if expression then simple_expression else expression

simple_expression :
   logical_term { or logical_term }

logical_term :
   logical_factor { and logical_factor }

logical_factor :
   [ not ] relation

relation :
   arithmetic_expression [ rel_op arithmetic_expression ]

rel_op :
   "<" | "<=" | ">" | ">=" | "==" | "<>"

arithmetic_expression :
   [ add_op ] term { add_op term }

add_op :
   "+" | "-"

term :
   factor { mul_op factor }

mul_op :
```

```
   "*" | "/"

factor :
   primary [ "^" primary ]

primary :
   UNSIGNED_NUMBER
 | STRING
 | time
 | false
 | true
 | component_reference
 | name "(" { function_arguments } ")"
 | "(" expression ")"
 | "[" row_expression { ";" row_expression } "]"

name :
   IDENT [ "." name ]

component_reference :
   IDENT [ subscripts ] [ "." component_reference ]

row_expression :
   expression { "," expression }

function_arguments :
   expression { "," expression }
 | IDENT "=" expression { "," IDENT "=" expression }

subscripts :
   "[" subscript { "," subscript } "]"

subscript :
   ":" | expression [ ":" expression [ ":" expression ] ]

comment :
   [ STRING ] [ annotation ]

annotation :
   annotation class_modification
```

Appendix B.2. Modelica Semantics

Overview

The Modelica language is specified by means of a set of rules for translating a model described in Modelica to the corresponding model described as a flat hybrid DAE. The key issues of the translation (or instantiation in object-oriented terminology) are:

- Expansion of inherited base classes
- Parameterization of base classes, local classes and components
- Generation of connection equations from **connect** statements

The flat hybrid DAE form consists of:

- Declarations of constants, parameters and variables.
- Differential and algebraic equations.
- Instantaneous equations.

The semantic specification should be read together with the Modelica grammar. Non-normative text, i.e., examples and comments, are enclosed in *[ ]*, comments are set in *italics.*

Fundamentals

A class is instantiated in a context which consists of an environment and an ordered set of parents. The environment contains arguments which modify elements of the class (e.g., parameter changes). The environment is built by merging class modifications. The set of parents are the lexically enclosing classes and the set of top-level classes; the set of parents are used for looking up names of types etc.

[Example:

```
class C1 ... end C1;

class C2 ... end C2;

class C3
  Real x=3;
  C1 y;
end C3;
```

The (artificial) parent of class C3 is a set containing C1 and C2. The parent of the declaration of `x` *is the partially instantiated class C3.]*

Lookup is done by searching parents from the innermost class outwards. *[For example, in the declaration of* `y`*, C1 is not found in C3, so the lookup continues in the parent of C3 (which contains C1 and C2).]*

Names are typically looked up in a partially instantiated class. *[This means that a declaration can refer to a name previously inherited.]*

The name of a declared element shall not have the same name as any other element in its parent class or any of the parent class' base classes.

The elements of a class are instantiated in the order of declaration.

[The following larger example demonstrates several aspects:

```
class C1
  class C11
    parameter Real x;
  end C11;
end C1;

class C2
  class C21
    ...
  end C21;
end C2;

class C3
  extends C1;
  C11 t(x=3);          // ok, C11 has been inherited from C1
  C21 u;               // error, C21 has not yet been inherited
  extends C2;
end C3;
```

The environment of the declaration of t is (x=3). The environment is built by merging class modifications, as shown by:

```
class C1
  parameter Real a;
end C1;

class C2
  parameter Real b;
end C2;

class C3
  parameter Real x1;        // No default value
  parameter Real x2 = 2;    // Default value 2
  parameter C1 x3;          // No default value for x3.a
  parameter C1 x4(a=4);     // x4.a has default value 4
  extends C1;               // No default value for inherited element
  extends C2(b=6);          // Inherited b has default value 6
end C3;

class C4
  extends C3(x2=22, x3(a=33), x4(a=44), C1(a=55), b=66);
end C4;
```

Outer modifications override inner modifications, e.g., `b=66` *overrides the nested class modification of* `extends C2(b=6)`*. This is known as merging of modifications:* `merge((b=66), (b=6))` *becomes* `(b=66)`*.*

An instantiation of class C4 will give an object with the following variables:

Variable	*Default value*
x1	*none*
x2	*22*
x3.a	*33*
x4.a	*44*
a	*55*
b	*66*

The last argument of the C3 modification shows that an inherited element (here, `b=66`*) can be directly referred to, without specifying its base class as in* `C1(a=55)`*.]*

Subtyping and type equivalence

For any classes S and C, S is a supertype of C and C is a subtype of S if they are equivalent or if:

- every public declaration element of S also exists in C (according to their names)
- those element types in S are supertypes of the corresponding element types in C.

A base class is the class referred to in an extends clause. The class containing the extends clause is called the derived class. *[All base classes of C are supertypes of C, but other classes not related by inheritance can also be supertypes of C.]*

Two types T and U are equivalent if:

- T and U denote the same built-in type (one of RealType, IntegerType, StringType or BooleanType), or
- T and U are classes, T and U contain the same public declaration elements (according to their names), and the elements types in T are equivalent to the corresponding element types in U.

Short class definition

A class definition of the form

```
class IDENT1 = IDENT2 class_modification ;
```

is identical to the longer form

```
class IDENT1
  extends IDENT2 class_modification ;
end IDENT1;
```

Local class definition

The local class is instantiated with the partially instantiated parent of the local class. The environment is the modification of any parent class element modification with the same name as the local class, or an empty environment.

The instantiated local class becomes an element of the instantiated parent class.

[The following example demonstrates parameterization of a local class:

```
class C1
  class Voltage = Real(unit="V");
  Voltage v1, v2;
end C1;

class C2
  extends C1(Voltage(unit="kV"));
end C2;
```

Instantiation of class C2 yields a local instance of class Voltage with unit "kV". The variables v1 and v2 thus have unit "kV".]

Extends clause

The name of the base class is looked up in the partially instantiated parent of the extends clause. The found base class is instantiated with a new environment and the partially instantiated parent of the extends clause. The new environment is the result of merging

- arguments of all parent environments that match names in the instantiated base class
- the modification of a parent element-modification with the same name as the base class
- the optional class modification of the extends clause

in that order.

[Examples of the three rules are given in the following example:

```
class A
  parameter Real a, b;
end A;

class B
  extends A(b=3);              // Rule #3
end B;

class C
  extends B(a=1, A(b=2));      // Rules #1 and #2
end C;
```

]

The elements of the instantiated base class become elements of the instantiated parent class.

[From the example above we get the following instantiated class:

```
class Cinstance
  parameter Real a=1;
  parameter Real b=2;
end Cinstance;
```

The ordering of the merging rules ensures that, given classes A and B defined above,

```
class C2
  B bcomp(b=1, A(b=2));
end C2;
```

yields an instance with `bcomp.b=1`*, which overrides* `b=2`*.]*

The declaration elements of the instantiated base class shall either

- Not already exist in the partially instantiated parent class *[i.e., have different names]* .
- Have a type identical to the type of any element of the instantiated parent class with the same name. In this case, the element of the instantiated base class is ignored.

Otherwise the model is incorrect.

[The second rule says that if an element is inherited multiple times, the first inherited element overrides later inherited elements:

```
class A
  parameter Real a, b;
end A;

class B
  extends A(a=1);
  extends A(b=2);
end B;
```

Class B is well-formed and yields an instantiated object with elements `a` *and* `b` *inherited from the first extends clause:*

```
class Binstance
  parameter Real a=1;
  parameter Real b;
```

```
end Binstance;
```

]

Equations of the instantiated base class that are syntactically equivalent to equations in the instantiated parent class are discarded.

Component clause

If the type specifier of the component denotes a built-in type (RealType, IntegerType, etc.), the instantiated component has the same type and argument.

If the type specifier of the component does not denote a built-in type, the name of the type is looked up in the partially instantiated parent. The found type is instantiated with a new environment and the partially instantiated parent of the component. The new environment is the result of merging

- the modification of parent element-modification with the same name as the component
- the modification of the component declaration

in that order.

Equation

The instantiated equation is identical to the non-instantiated equation.

Names in an equation shall be found by looking up in the partially instantiated parent of the equation.

Redeclaration

A **redeclare** construct replaces the declaration of an extends clause, local class or component in the modified element with another declaration. The type specified in the redeclaration shall be a subtype of the type in the original declaration.

The element modifications of the redeclaration and the original declaration are merged in the usual way.

[Example:

```
class A
  parameter Real x;
end A;

class B
  parameter Real x, y;    // B is a subtype of A
end B;

class C
  A a(x=1);
end C;

class D
  extends C(redeclare B a(y=2));
end D;
```

which effectively yields a class D2 with the contents

```
class D2
  B a(x=1, y=2);
end D2;
```

]

The following additional constraints apply to redeclarations:

- an element declared as **final** cannot be redeclared
- an element declared as **constant** can only be redeclared with **constant**
- an element declared as **parameter** can only be redeclared with **parameter** or **constant**
- a local **function** can only be redeclared as **function**

Modelica does not allow a protected element to be redeclared as public, or a public element to be redeclared as protected.

Generation of connection equations

The two main tasks are to:

- Build connection sets from **connect** statements.
- Generate equations for the complete model.

For every use of the connect operator

```
connect(a, b);
```

the components `a` and `b` form a connection set. If a or b already occur in a previously encountered connection set, these sets are merged to form one connection set. Composite connector types are broken down into primitive components. Each connection set is used to generate equations for across and through (zero-sum) variables of the form

```
a1 = a2 = ... = an;
z1 + z2 + (-z3) + ... + zn = 0;
```

In order to generate equations for through variables *[using the `flow` prefix]*, a connector is regarded as an outer connector with respect to its parent M if it is an element of M. It is an inner connector if it is an element of a component of M. The sign used for the connector variable z_i above is +1 for inner connectors and -1 for outer connectors *[`z3` in the example above]*.

A connection set shall contain either only flow variables or only non-flow variables.

Appendix B.3. Unit Expressions

Unless otherwise stated, the syntax and semantics of unit expressions in Modelica are conform with the international standards ISO 31/0-1992 "General principles concerning quantities, units and symbols" and ISO 1000-1992 "SI units and recommendations for the use of their multiples and of certain other units". Unfortunately, neither these two standards nor other existing or emerging ISO standards define a formal syntax for unit expressions. There are recommendations and Modelica exploits them.

Examples for the syntax of unit expressions used in Modelica: "N.m", "kg.m/s2", "kg.m.s-2"

"1/rad", "mm/s".

The Syntax of Unit Expressions

```
unit_expression:
   unit_numerator [ "/" unit_denominator ]

unit_numerator:
   "1" | unit_factors |  "(" unit_expression ")"

unit_denominator:
   unit_factor |  "(" unit_expression ")"
```

The unit of measure of a dimension free quantity is denoted by "1". The ISO standard does not define any precedence between multiplications and divisions. The ISO recommendation is to have at most one division, where the expression to the right of "/" either contains no multiplications or is enclosed within parentheses. It is also possible to use negative exponents, for example, "J/(kg.K)" may be written as "J.kg-1.K-1".

```
unit_factors:
   unit_factor [ unit_mulop  unit_factors ]

unit_mulop:
   "."
```

The ISO standard allows that a multiplication operator symbol is left out. However, Modelica enforces the ISO recommendation that each multiplication operator is explicitly written out in formal specifications. For example, Modelica does not support "Nm" for newtonmeter, but requires it to written as "N.m".

The preferred ISO symbol for the multiplication operator is a "dot" a bit above the base line: "·". Modelica supports the ISO alternative ".", which is an ordinary "dot" on the base line.

```
unit_factor:
   unit_operand [ unit_exponent ]

unit_exponent:
   [ "+" | "-" ] integer
```

The ISO standard does not define any operator symbol for exponentiation. A unit_factor consists of a unit_operand possibly suffixed by a possibly signed integer number, which is interpreted as an exponent. There must be no spacing between the unit_operand and a possible unit_exponent.

```
unit_operand:
   unit_symbol | unit_prefix unit_symbol

unit_prefix:
  Y | Z | E | P | T | G | M | k | h | da | d | c | m | u | p | f | a | z
```

A unit_symbol is a string of letters. A basic support of units in Modelica should know the basic and derived units of the SI system. It is possible to support user defined unit symbols. In the base version Greek letters is not supported, but full names must then be written, for example "Ohm".

A unit_operand should first be interpreted as a unit_symbol and only if not successful the second alternative assuming a prefixed operand should be exploited. There must be no spacing between the unit_symbol and a possible unit_prefix. The value of the prefixes are according to the ISO standard. The letter "u" is used as a symbol for the prefix micro.

Examples

- The unit expression "m" means meter and not milli (10^{-3}), since prefixes cannot be used in isolation. For millimeter use "mm" and for squaremeter, m^2, write "m2".
- The expression "mm2" means $mm^2 = (10^{-3}m)^2 = 10^{-6}m^2$. Note that exponentiation includes the prefix.

  The unit expression "T" means Tesla, but note that the letter "T" is also the symbol for the prefix tera which has a multiplier value of 10^{12}.

Appendix B.4. Restricted Classes

The keyword **class** can be replaced by one of the following keywords: **record**, **type**, **connector**, **model**, **block**, **package** or **function**. Certain restrictions will then be imposed on the content of such a definition. The following table summarizes the restrictions.

record	No equations are allowed in the definition or in any of its components. May not be used in connections.
type	May only be extension to the predefined types, records or matrix of type.
connector	No equations are allowed in the definition or in any of its components.
model	May not be used in connections.
block	Fixed causality, input-output block. Each component of an interface must either have Causality equal to Input or Output. May not be used in connections.
package	May only contain declarations of classes and constants.
function	Same restrictions as for block. Additional restrictions: no equations, only one algorithm section.

Appendix B.5. Summary of Prefixes

The following prefixes are available to *class declarations*: **partial** (needs to extended), **final** (can not be extended), **replaceable** (a local class which may be redeclared).

A *component clause* may have the prefix **final** (the class of a component can not be exchanged).

A *modification* may contain the prefixes **final** (can not be modified anymore), [**final**] **redeclare** (the class of a component is exchanged) and [**final**] **redeclare class** (or restricted class) (a replaceable class is redeclared).

It should be noted that the **final** and **partial** prefixes does not change the semantics of a valid model.

Appendix B.6. Variable Attributes

The attributes of the predefined variable types are described below with Modelica syntax although they are predefined. The definitions use basic types RealType, IntegerType, BooleanType and StringType correponding to machine representations.

```
final type Real
  RealType value;                       // Accessed without dot-nota
  parameter StringType  quantity    = "";
```

```
    parameter StringType  unit        = ""  "Unit used in equations";
    parameter StringType  displayUnit = ""  "Default display unit";
    parameter RealType    min=-Inf, max=+Inf;  // Inf denotes a large
    parameter RealType    start = 0;           // Initial and restart

  equation
    assert(value >= min and value <= max, "Variable value out of limit
  end Real;

  final type Integer
    IntegerType value;                   // Accessed without dot-nota
    parameter IntegerType min=-Inf max=+Inf;
    parameter IntegerType start = 0;     // Initial and restart value

  equation
    assert(value >= min and value <= max, "Variable value out of limit
  end Integer;

  final type Boolean
    BooleanType value;                  // Accessed without dot-notat
    parameter BooleanType start = false; // Initial and restart value
  end Boolean;

  final type String
    StringType value;                  // Accessed without dot-notati
    parameter StringType start = "";   // Initial and restart value
  end String;
```

Appendix B.7. External Function Interface

The purpose is to allow calls to functions defined outside of the Modelica language. The design goals were:

- C functions are used as the least common denominator. It is planned that other languages (C++, Fortran) will be supported in the future too.
- A mapping of argument types from Modelica to the target language should be defined.
- The mapping should be "natural" in the sense that there is a mapping from Modelica to standard libraries of the target language.

It should be possible to specify inverse and Jacobian functions. Details will be specified in a future Modelica release.

The format of an external function declaration is as follows.

```
  function IDENT
    [ input-declarations ]
    [ output-declaration ]

    external

  end IDENT;
```

Examples of Modelica function declarations:

```
  function log
    input  Real x;
    output Real y;
    external
```

```
end log;

function PolynomialEvaluator2
  input  Real a[:];
  input  Real x;
  output Real y;
  external
end PolynomialEvaluator2;

function Force3D
  input     Real c=1.0;
  input     Real s;
  output    Real f[3];
  external
end Force3D;
```

The corresponding declarations in the C language are:

```
extern double log(double x);
extern double PolynomialEvaluator2(double t* a, size_t dim1, double
extern void   Force3D(double c, double s, double *f, size_t dim1);
```

Mapping of argument types

The arguments of the external function are declared in the same order as in the Modelica declaration. The single Modelica function output parameter specifies the return type of the external function.

Simple types

Arguments of **simple** types are by default mapped as follows:

Modelica	C	
	Input	Output (return value)
Real	`double`	`double`
Integer	`int`	`int`
Boolean	`int`	`int`
String	`const char *`	`const char *`

Strings are nul-terminated to facilitate calling of C functions.

Arrays

Arrays of simple types are mapped to an argument of the simple type, followed by n arguments of type `size_t` with the corresponding array dimensions. The type `size_t` is a C unsigned integer type. Storage for arrays as return values is allocated by the calling routine, so the dimensions of the returned array is fixed.

Arrays are stored in column-major order according to the Fortran conventions, in order to be compatible with most standard numerical libraries.

Modelica	C
	Input and output
T[*dim1*]	*T* *, `size_t` *dim1*
T[*dim1*, *dim2*]	*T* *, `size_t` *dim1*, `size_t` *dim2*
T[...]	*T* *, `size_t` *dim1*, ..., `size_t` *dimn*

Records

A Modelica record class that contains simple types, other record elements, or arrays with fixed dimensions thereof, are mapped as follows:

- The record class is represented by a struct in C.
- Each element of the Modelica record is mapped to its corresponding C representation. The elements of the Modelica record class are declared in the same order in the C struct.
- Arrays are mapped to the corresponding C array.

For example,

```
record R
  Real x;
  Integer y[10];
  Real z;
end R;
```

is mapped to

```
struct R {
  double x;
  int    y[10];
  double z;
};
```

Appendix C. Modelica Standard Library

Modelica seeks to influence the trivial decisions of model design process by providing package **Modelica**, an extensive standard library of **type** and **interface** definitions which is always available with a Modelica translator. If, as far as possible, standard quantity types and connectors are relied on in modeling work, model compatibility and thereby reuse is enhanced. Achieving model compatibility, without having to resort to explicit coordination of modeling activities, is essential to the formation of globally accessible libraries. Naturally, a modeller is not required to use the standard library and may also add any number of local base definitions.

The library will be amended and revised as part of the ordinary language revision process. It is expected that informal standard base classes will develop in various domains and that these gradually will be incorporated into the Modelica standard library.

The type definitions in the library are based on ISO 31-1992. Several ISO quantities have long names that tend to become awkward in practical modeling work. For this reason, shorter alias-names are also provided if necessary. Using, e.g., "ElectricPotential" repeatedly in a model becomes cumbersome and therefore "Voltage" is also supplied as an alternative.

The standard library is not limited to pure SI units. Whenever common engineering practice uses a different set of (possibly inconsistent) units, corresponding quantities will be allowed in the standard library, for example English units. It is also frequently common to write models with respect to scaled SI units in order to improve the condition of the model equations or to keep the actual values around one for easier reading and writing of numbers.

The connectors and partial models will get predefined graphical attributes in order that the basic visual appearance is the same in all Modelica based systems.

The Modelica package is still under development. This appendix displays the draft status as of September 1997.

```
package Modelica
/* The Modelica package is a standardized, pre-defined package,
   that is shipped together with a Modelica translator. The package
   provides constants, types, connectors, partial models and some
   often used model components in various disciplines. Especially,
   the following sub-packages are available:

   SIunit   : Types defining SIunits of ISO 1000.
   Constant : Mathematical and physical constants.
   Interface: Basic interfaces in various disciplines
   Signal   : Real and Boolean signal generators.


   The following conventions are used in the whole package:

   - Class and instance names are written in upper and lower case
     letters, e.g., "ElectricCurrent". An underscore is only used
     at the end of a name to characterize a lower or upper index,
     e.g., body_low_up.

   - Type names start always with an upper case letter. Instance names s
     always with a lower case letter with only a few exceptions accordir
     common engineering practice, such as "T" for a temperature instance

   - Usually, SIunits are used via pre-defined SIunit types.

   - Preferred instance names for connectors:
       p,n: positive and negative side of a partial model.
       a,b: side "a" and side "b" of partial model,
            if the two connectors are completely equivalent.
*/


package SIunit

/* This package provides predefined types based on the international sta
   on units (ISO 31-1992 "General principles concerning quantities, unit
   symbols" and ISO 1000-1992 "SI units and recommendations for the use
   their multiples and of certain other units"). The ordering of the typ
   declarations follows ISO 31. The naming of  the types follows the fol
   convention:

   - Modelica quantity names are defined according to the recommendatior
     ISO 31. Some of these name are rather long, such as
     "ThermodynamicTemperature". Shorter alias names are defined in
     appropriate subpackages, e.g., "type Temp_K = ThermodynamicTemperat

   - Modelica units are defined according to the SI base units without
     multiples (only exception "kg").

   - For some quantities, more convenient units for an engineer are defi
     "displayUnit", i.e., the default unit for display purposes
     (e.g., displayUnit="deg" for quantity="Angle").

   - The type name is identical to the quantity name, following
     the convention of type names.
```

```
   - All quantity and unit attributes are defined as final in order
     that they cannot be redefined to another value.

   - Some quantities, which are obviously also important but are not
     explicitly mentioned in the ISO 1000 standard, such as
     "AngularAcceleration", are also included.
*/

// Part 1: Space and time
   type Angle                = Real(final quantity="Angle",
                                    final unit    ="rad",
                                    Displayunit   ="deg");
   type SolidAngle           = Real(final quantity="SolidAngle",
                                    final unit    ="sr");
   type Length               = Real(final quantity="Length",
                                    final unit    ="m");
   type Area                 = Real(final quantity="Area",
                                    final unit    ="m2");
   type Volume               = Real(final quantity="Volume",
                                    final unit    ="m3");
   type Time                 = Real(final quantity="Time",
                                    final unit    ="s");
   type AngularVelocity      = Real(final quantity="AngularVelocity",
                                    final unit    ="rad/s");
   type Velocity             = Real(final quantity="Velocity",
                                    final unit    ="m/s");
   type AngularAcceleration = Real(final quantity="AngularAcceleration",
                                    final unit    ="rad/s2");
   type Acceleration         = Real(final quantity="Acceleration",
                                    final unit    ="m/s2");

// Part 2: Periodic and related phenomens
   //...

// Part 3: Mechanics
   type Mass                = Real(final quantity="Mass",
                                   final unit    ="kg", min=0);
   type Density             = Real(final quantity="Density",
                                   final unit    ="kg/m3", min=0);
   type LinearDensity       = Real(final quantity="LinearDensity",
                                   final unit    ="kg/m", min=0);
   type MomentOfInertia     = Real(final quantity="MomentOfInertia",
                                   final unit    ="kg*m^2");
   type Momentum            = Real(final quantity="Mass",
                                   final unit    ="kg.m/s");
   type Force               = Real(final quantity="Force",
                                   final unit    ="N");
   type AngularMomentum     = Real(final quantity="Mass",
                                   final unit    ="kg.m2/s");
   type MomentOfForce       = Real(final quantity="MomentOfForce",
                                   final unit    ="N.m");
   type Pressure            = Real(final quantity="Pressure",
                                   final unit    ="Pa", min=0);
   type NormalStress        = Real(final quantity="NormalStress",
                                   final unit    ="Pa");
   type DynamicViscosity    = Real(final quantity="DynamicViscosity",
                                   final unit    ="Pa.s", min=0);
   type KinematicViscosity = Real(final quantity="KinematicViscosity",
                                   final unit    ="m2/s", min=0);
   type SurfaceTension      = Real(final quantity="SurfaceTension",
```

```
                              final unit    ="N/m");
type Energy             = Real(final quantity="Energy",
                              final unit    ="J");
type Power              = Real(final quantity="Power",
                              final unit    ="W");

// Part 4: Heat
type ThermodynamicTemperature = Real(final quantity="ThermodynamicTe
                                    final unit    ="K", min=0,
                                    Displayunit   ="degC");
type CelsiusTemperature       = Real(final quantity="CelsiusTemperat
                                    final unit    ="degC", min = -2

type LinearExpansionCoefficient       = Real(final quantity=" Linear
                                            final unit ="1/K");
type CubicExpansionCoefficient        = Real(final quantity="CubicEx
                                            final unit ="1/K");
type RelativePressureCoefficient      = Real(final quantity="Relativ
                                            final unit ="1/K");
type PressureCoefficient              = Real(final quantity="Pressur
                                            final unit ="Pa/K");
type IsothermalCompressibility        = Real(final quantity="Isother
                                            final unit ="1/Pa");
type IsentropicCompressibility        = Real(final quantity="Isentro
                                            final unit ="1/Pa");
type Heat                             = Energy;
type HeatFlowRate                     = Real(final quantity="HeatFlo
                                            final unit ="W");
type DensityOfHeatFlowRate            = Real(final quantity="Density
                                            final unit ="W/m^2");
type ThermalConductivity              = Real(final quantity="Thermal
                                            final unit ="W/(m.K)");
type CoefficientOfHeatTransfer        = Real(final quantity="Coeffic
                                            final unit ="W/(m^2.K)"
type SurfaceCoefficientOfHeatTransfer = Real(final quantity="Surface
                                            final unit ="W/(m^2.K)"
type ThermalInsulance                 = Real(final quantity="Thermal
                                            final unit ="m^2.K/W");
type ThermalResistance                = Real(final quantity="Thermal
                                            final unit ="K/W");
type ThermalConductance               = Real(final quantity="Thermal
                                            final unit ="W/K");
type ThermalDiffusivity               = Real(final quantity="Thermal
                                            final unit ="m^2/s");
type HeatCapacity                     = Real(final quantity="HeatCap
                                            final unit ="J/K");
type SpecificHeatCapacity             = Real(final quantity="Specifi
                                            final unit ="J/(kg.K)")

/* The specific heat capacity is most often taken in a "direction"
   i. e. at constant pressure or constant volume. which one is meant
   should be specified in the appropriate aliases
*/

type RatioOfSpecificHeatCapacities = Real(final quantity="RatioOfSpe
                                         final unit ="1");
type IsentropicExponent            = Real(final quantity="Isentropic
                                         final unit ="1");
type Entropy                       = Real(final quantity="Entropy",
                                         final unit ="J/K");
type SpecificEntropy               = Real(final quantity="SpecificEn
```

```
                                          final unit ="J/(kg.K)");
   type SpecificEnergy                = Real(final quantity="SpecificEn
                                          final unit ="J/kg");

   /* In thermodynamics, energy comes in many flavors. The ones defined
      are defined as aliases to the basic one. All of these energy forms
      defined in a specific, i. e. divided by mass version.
   */

   type ThermodynamicEnergy         = Energy;
   type HelmholtzFreeEnergy         = Energy;
   type GibbsFreeEnergy             = Energy;
   type Enthalpy                    = Energy;

   type SpecificThermodynamicEnergy = SpecificEnergy;
   type SpecificHelmholtzFreeEnergy = SpecificEnergy;
   type SpecificGibbsFreeEnergy     = SpecificEnergy;
   type SpecificEnthalpy            = SpecificEnergy;


   type PlanckFunction  = Real(final quantity="PlanckFunction",
                               final unit ="J/kg");


// Part 5: Electricity and magnetism
   type ElectricCurrent   = Real(final quantity="ElectricCurrent",
                                 final unit    ="A");
   type ElectricCharge    = Real(final quantity="ElectricCharge",
                                 final unit    ="C");
   type ElectricPotential = Real(final quantity="ElectricPotential",
                                 final unit    ="V");
   type Capacitance       = Real(final quantity="Capacitance",
                                 final unit    ="F", min=0);
   type Inductance        = Real(final quantity="Inductance",
                                 final unit    ="H", min=0);
   type Resistance        = Real(final quantity="Resistance",
                                 final unit    ="Ohm", min=0);
   type Conductance       = Real(final quantity="Conductance",
                                 final unit    ="S", min=0);
   //...


// Part 6: Light and related electromagnetic radiations
   type LuminousIntensity = Real(final quantity="LuminousIntensity",
                                 final unit    ="cd");
   //...

// Part 7: Acoustics
   //...

// Part 8: Physical chemistry and molecular physics
   type AmountOfSubstance = Real(final quantity="AmountOfSubstance",
                                 final unit    ="mol", min=0);
   //...

// Part 9: Atomic and nuclear physics
   //...

// Part 10: Nuclear reactions and ionizing radiations
   //...
```

```
// Part 11: Characteristic numbers
   // Momentum transport
      type ReynoldsNumber = Real(final quantity="ReynoldsNumber",
                                 final unit ="1");
      type EulerNumber    = Real(final quantity="EulerNumber",
                                 final unit ="1");
      type FroudeNumber   = Real(final quantity="FroudeNumber",
                                 final unit ="1");
      type GrashofNumber  = Real(final quantity="GrashofNumber",
                                 final unit ="1");
      type WeberNumber    = Real(final quantity="WeberNumber",
                                 final unit ="1");
      type MachNumber     = Real(final quantity="MachNumber",
                                 final unit ="1");
      type KnudsenNumber  = Real(final quantity="KnudsenNumber",
                                 final unit ="1");
      type StrouhalNumber = Real(final quantity="StrouhalNumber",
                                 final unit ="1");

   // Transport of heat
      type FourierNumber  = Real(final quantity="FourierNumber",
                                 final unit ="1");
      type PecletNumber   = Real(final quantity="PecletNumber",
                                 final unit ="1");
      type RayleighNumber = Real(final quantity="RayleighNumber",
                                 final unit ="1");
      type NusseltNumber  = Real(final quantity="NusseltNumber",
                                 final unit ="1");
      type BiotNumber     = NusseltNumber;   // The name Biot number, Bi
                                             // when the Nusselt number
                                             // for convective transport
      type StantonNumber  = Real(final quantity="StantonNumber",
                                 final unit ="1");

   // Constants of matter
      type PrandtlNumber = Real(final quantity="PrandtlNumber",
                                final unit ="1");
      type SchmidtNumber = Real(final quantity="SchmidtNumber",
                                final unit ="1");
      type LewisNumber   = Real(final quantity="Number",
                                final unit ="1");

// Part 12: Solid state physics
   //...

end SIunit;


package Constant

/* This package provides often needed constants */
extends SIunit;

// Mathematical constants
   constant Real PI = 3.14159265358979;
   constant Real E  = 2.71828182845904;

/* Constants of nature
   (from: E.R. Cohen, and B.N. Taylor: The 1986 Adjustment of the Fundan
          Physical Constants, CODATA Bulletin, Pergamon: Elmsford, NY, 1
```

```
          see also: http://physics.nist.gov/PhysRefData/codata86/article
                    http://physics.nist.gov/PhysRefData/codata86/codata8
*/

   constant Real         N_A     (final unit="mol-1")
                                 = 6.0221367e23  "Avogadro constant";
   constant Velocity     C       = 299792458     "Velocity of light in v
   constant Real         G       (final unit="m3.kg-1.s-2")
                                 = 6.67259e-11   "Universal gravity cons
   constant Acceleration G_EARTH = 9.81          "Gravity acceleration o
   constant Real         H       (final unit="J.s")
                                 = 6.6260755e-34 "Plancks constant";
   constant Real         K       (final unit="J.K-1")
                                 = 1.380658e-23  "Boltzmann constant";
   constant Real         R0      (final unit="J.mol-1.K-1")
                                 = 8.314510      "Universal gas constant
   constant Real         SIGMA   (final unit="W.m-2.K-4")
                                 = 5.67051e-8    "Stefan Boltzmann const
   constant Real         T_ZERO  (final unit="degC")
                                 = -273.15       "Absolute zero temperat
// ...

end Constant;


package Interface

/* This package provides interface definitions, i.e., types, connectors a
   partial models, in various disciplines. It is organized in sub-packag

     Block         : Interfaces for input/output blocks.
     BondGraph     : Interfaces for bondgraphs.
     Electric      : Interfaces for electric systems.
     Mechanic      : Interfaces for mechanic systems.
     Thermodynamic: Interfaces for thermodynamic systems.
*/


package Block

/* This package provides types, connectors and partial models for
   input/output blocks.
*/
extends SIunit;

// Partial models for continuous input/output control blocks
   partial block SISO "Single input, single output (continuous) block"
     input  Real u  "Input signal";
     output Real y  "Output signal";
   end SISO;

   partial block MISO "Multiple input, single output (continuous) block"
     input  Real u[:]  "Input signal vector";
     output Real y    "Output signal";
   end MISO;

   partial block MIMO "Multiple input, multiple output (continuous) bloc
     input  Real u[:]  "Input signal vector";
     output Real y[:]  "Output signal vector";
   end MIMO;
```

```
   partial block MIMOs "Multiple input, single output (continuous) block
                       "with equal number of inputs and outputs"
     input  Real u[:]           "Input signal vector";
     output Real y[size(u,1)]  "Output signal vector";
   end MIMOs;

   partial block SO "Single output (continuous) block"
     output Real y  "Output signal";
   end SO;

   partial block MO "Multiple output (continuous) block"
     output Real y[]  "Output signal vector";
   end MO;

// Partial models for Boolean input/output blocks
   partial block SISOb "Single input, single output (Boolean) block"
     input  Boolean u  "Input signal";
     output Boolean y  "Output signal";
   end SISOb;

   partial block MISOb "Multiple input, single output (Boolean) block"
     input  Boolean u[]  "Input signal vector";
     output Boolean y    "Output signal";
   end MISOb;

   partial block MIMOb "Multiple input, multiple output (Boolean) block'
     input  Boolean u[]  "Input signal vector";
     output Boolean y[]  "Output signal vector";
   end MIMOb;

   partial block MIMOsb "Multiple input, single output (Boolean) block"
                       "with equal number of inputs and outputs"
     input  Boolean u[]           "Input signal vector";
     output Boolean y[size(u,1)]  "Output signal vector";
   end MIMOsb;

   partial block SOb "Single output (Boolean) block"
     output Boolean y  "Output signal";
   end SOb;

   partial block MOb "Multiple output (Boolean) block"
     output Boolean y[]  "Output signal vector";
   end MOb;
end Block;


package BondGraph

/* This package provides types, connectors and partial models for
   bond graphs
*/
extends SIunit;

// Bond Graph power connector.
// Both effort and flow are "across" variables.

   connector BondPort "Bond Graph power port"
      Real e  "Effort variable";
      Real f  "Flow variable";
   end BondPort;
```

```
   partial model OnePortPassive "One port passive bond graph element"
      BondPort p "Generic power port p";
   equation
      assert(cardinality(p)==1, "Power ports have only one edge connecte
      assert(direction(p)  ==1, "Power direction towards element for pas
   end OnePortPassive;

   partial model OnePortEnergetic "One port storage element, being passi
      extends OnePortPassive;

      Real state "Conserved quantity";
   end OnePortEnergetic;

   partial model OnePortActive "One port active bond graph element: the
      BondPort p;
   equation
      assert(cardinality(p)== 1, "Power ports have only one edge connect
      assert(direction(p)  ==-1, "Power direction from the element for a
   end OnePortActive;

   partial model TwoPortPassive "Two port passive bond graph element"
      BondPort PowIn, PowOut;
   equation
      assert(cardinality(Powin) == 1, "Power ports have only one edge co
      assert(direction  (PowIn) ==+1, "power direction towards the eleme
      assert(cardinality(Powout)== 1, "Power ports have only one edge co
      assert(direction  (PowOut)==-1, "Power direction from the element
   end TwoPortPassive;

end BondGraph;


package Electric

/* This package providestypes, connectors and partial models for
   the electric domain.
*/
extends SIunit;

// Commonly used short names for electric types
   type Current = ElectricCurrent;
   type Charge  = ElectricCharge;
   type Voltage = ElectricPotential;

// Connector types for electric components
   connector Pin "Pin of an electric component"
     Voltage      v  "Potential at the pin";
     flow Current i  "Current flowing into the pin";
   end Pin;

// Partial models for electric components
   partial model TwoPin "Component with two electric pins"
     Pin     p  "Positive pin";
     Pin     n  "Negative pin";
     Voltage v  "Voltage drop between the two pins";
   equation
     v = p.v - n.v;
   end TwoPin;
```

```
   partial model TwoPort "Component with two electric ports"
     Pin     pl  "Positive pin of the left port";
     Pin     nl  "Negative pin of the left port";
     Pin     pr  "Positive pin of the right port";
     Pin     nr  "Negative pin of the right port";
     Voltage vl  "Voltage drop over the left port";
     Voltage vr  "Voltage drop over the right port";
   equation
     vl = pl.v - nl.v;
     vr = pr.v - nr.v;
   end TwoPort;
end Electric;



package Mechanic

/* This package provides types, connectors and partial models for
   the mechanic domain.
*/
extends SIunit;

// Commonly used short names for mechanic types
   type Position = Length;
   type Distance = Length(final min=0);
   type Inertia  = MomentOfInertia;
   type Torque   = MomentOfForce;

// Connector types for mechanic components
   connector TransVel  "1D translational mechanical flange cut on veloci
     Velocity   v  "Absolute velocity of the flange with respect to base
     flow Force f  "Cut-force directed into the flange to drive it";
   end TransVel;

   connector DriveVel  "1D rotational mechanical flange cut on velocity
     AngularVelocity w  "Absolute angular velocity of flange with respec
     flow Torque     t  "Cut-torque directed into the flange to drive it
   end DriveVel;

   connector TransPos "1D translational mechanical flange cut"
     Position     s  "Absolute position of flange with respect to base";
     Velocity     v  "Absolute velocity of flange with respect to base";
     Acceleration a  "Absolute acceleration of flange with respect to ba
     flow Force   f  "Cut-force directed into flange to drive it";
   end TransPos;

   connector DrivePos "1D rotational mechanical flange cut"
                      "for positional drive trains."
     Angle               r  "Absolute rotation angle of flange cut with
     AngularVelocity     w  "Absolute angular velocity of flange with re
     AngularAcceleration a  "Absolute angular acceleration of flange wit
                            "respect to base";
     flow Torque         t  "Cut-torque directed into flange to drive it
   end DrivePos;

   connector CutFrame "3D mechanical cut-frame for multibody systems"
     Real               S[3,3] "Rotation matrix describing the cut-fram
                               "with respect to the inertial frame";
     Position           r0[3]  "Vector from the origin of the inertial
                               "origin of the cut-frame, resolved in th
     Velocity           v[3]   "Absolute translational velocity of the
                               "resolved in the cut-frame ( v = S'*der(
```

```
      AngularVelocity     w[3]   "Absolute angular velocity of the cut-fr
                                 "resolved in the cut-frame ( w = vec(S'*
      Acceleration        a[3]   "Absolute translational acceleration of
                                 "resolved in the cut-frame ( a = S'*der(
      AngularAcceleration z[3]   "Absolute angular acceleration of the cu
                                 "resolved in the cut-frame ( z = S'*der(
      flow Force          f[3]   "Resultant cut-force acting at the origi
                                 "cut-frame, resolved in the cut-frame";
      flow Torque         t[3]   "Resultant cut-torque with respect to th
                                 "cut-frame, resolved in the cut-frame";
   end CutFrame;

// Partial models for mechanic components
   partial model TransVel2 "1D translational component with two cuts"
     TransVel a  "Cut a of component";
     TransVel b  "Cut b of component";
   end TransVel2;

   partial model DriveVel2 "1D rotational component with two cuts"
     DriveVel a  "Flange a of component";
     DriveVel b  "Flange b of component";
   end DriveVel2;

   partial model TransPos2 "1D translational component with two cuts"
                             "for positional drive trains."
     TransPos a  "Cut a of component";
     TransPos b  "Cut b of component";
   end TransPos2;

   partial model DrivePos2 "1D rotational component with two cuts"
                             "for positional drive trains."
     DrivePos a  "Flange a of component";
     DrivePos b  "Flange b of component";
   end DrivePos2;

   partial model CutFrame2 "Multi-body system component with two cut fra
     CutFrame a  "cut frame a";
     CutFrame b  "cut frame b";
   end CutFrame2;
end Mechanic;


package Thermodynamic

/* Connector types for thermodynamical components. This is a minimum
   set! Defining more is not difficult, but only useful if a library
   based on them is provided as well. Shorthands for basic types
   used here are provided as well.
*/

// Short hands
   type HeatFlux = HeatFlowRate;
   type Temp_K   = ThermodynamicTemperature;
   type Temp_C   = CelsiusTemperature;

// connectors
   connector TQ  "Heat exchange interface"
     Temp_C         T  "Temperature";
     flow HeatFlux  q  "Transported heat into interface";
   end TQ;
```

```
   connector MT  "Single directional flow of tempered fluid, no pressure
     flow MassFlow  m_dot  "Massflow into port";
     Temp_C         T      "Fluid temperature";
   end MT;

   connector PM  "Bidirectional flow of a fluid"
     Pressure       p      "Fluid total pressure";
     flow MassFlow  m_dot  "Massflow into port";
   end PM;

   connector PMT  "Single directional flow of tempered fluid"
     Pressure       p      "Fluid total pressure";
     flow MassFlow  m_dot  "Massflow into port";
     Temp_C         T      "Fluid temperature";
   end PMT;

   connector PMH  "Single directional flow of tempered fluid"
     Pressure          p      "Fluid total pressure";
     flow MassFlow     m_dot  "Massflow into port";
     SpecificEnthalpy  h      "Fluid enthalpy";
   end PMH;

   connector PMTQ  "Bidirectional flow of tempered fluid"
     Pressure       p       "Fluid total pressure";
     flow MassFlow  m_dot   "Massflow into port";
     Temp_C         T       "Fluid temperature";
     flow HeatFlux  q       "Heat convected by fluid into port";
   end PMTQ;

   connector PMHQ  "Bidirectional flow of tempered fluid"
     Pressure          p      "Fluid total pressure";
     flow Massflow     m_dot  "Massflow into port";
     SpecificEnthalpy  h      "Fluid enthalpy";
     flow HeatFlux     q      "Heat convected by fluid into port";
   end PMHQ;

end Thermodynamic;


end Interface;

end Modelica;
```