Multi-bond Graphs

- We shall today look at vectors of bonds, called multi-bonds.
- Especially when dealing with 2D and 3D mechanics, the d'Alembert principle must be applied to each degree of freedom separately.
- Each equation looks structurally the same.
- This leads naturally to a demand for multi-bond graphs.

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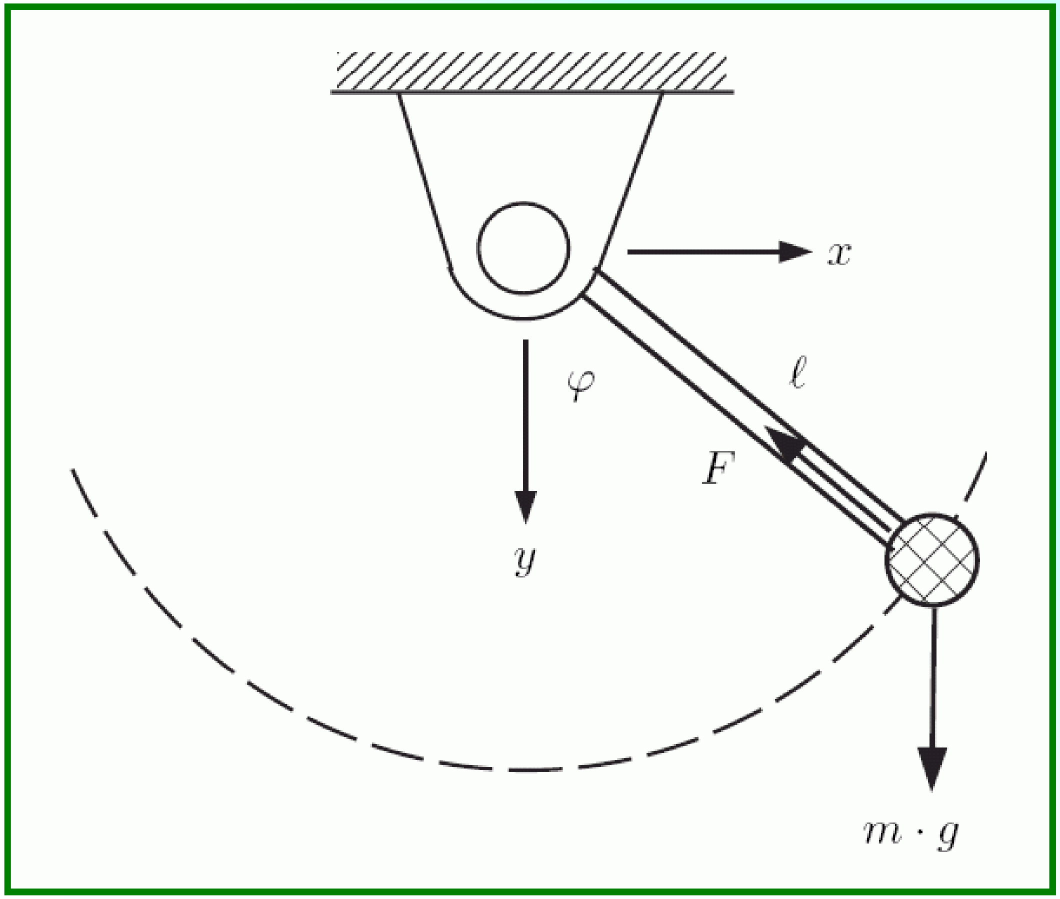
A Planar Pendulum

- Let us model the following planar pendulum:



$$
\begin{aligned}
m \cdot \frac{dv_x}{dt} &= -\frac{F \cdot x}{\ell} \\
m \cdot \frac{dv_y}{dt} &= m \cdot g - \frac{F \cdot y}{\ell} \\
\frac{dx}{dt} &= v_x \\
\frac{dy}{dt} &= v_y \\
\boxed{x^2 + y^2 = \ell^2}
\end{aligned}
$$

Holonomic Constraint

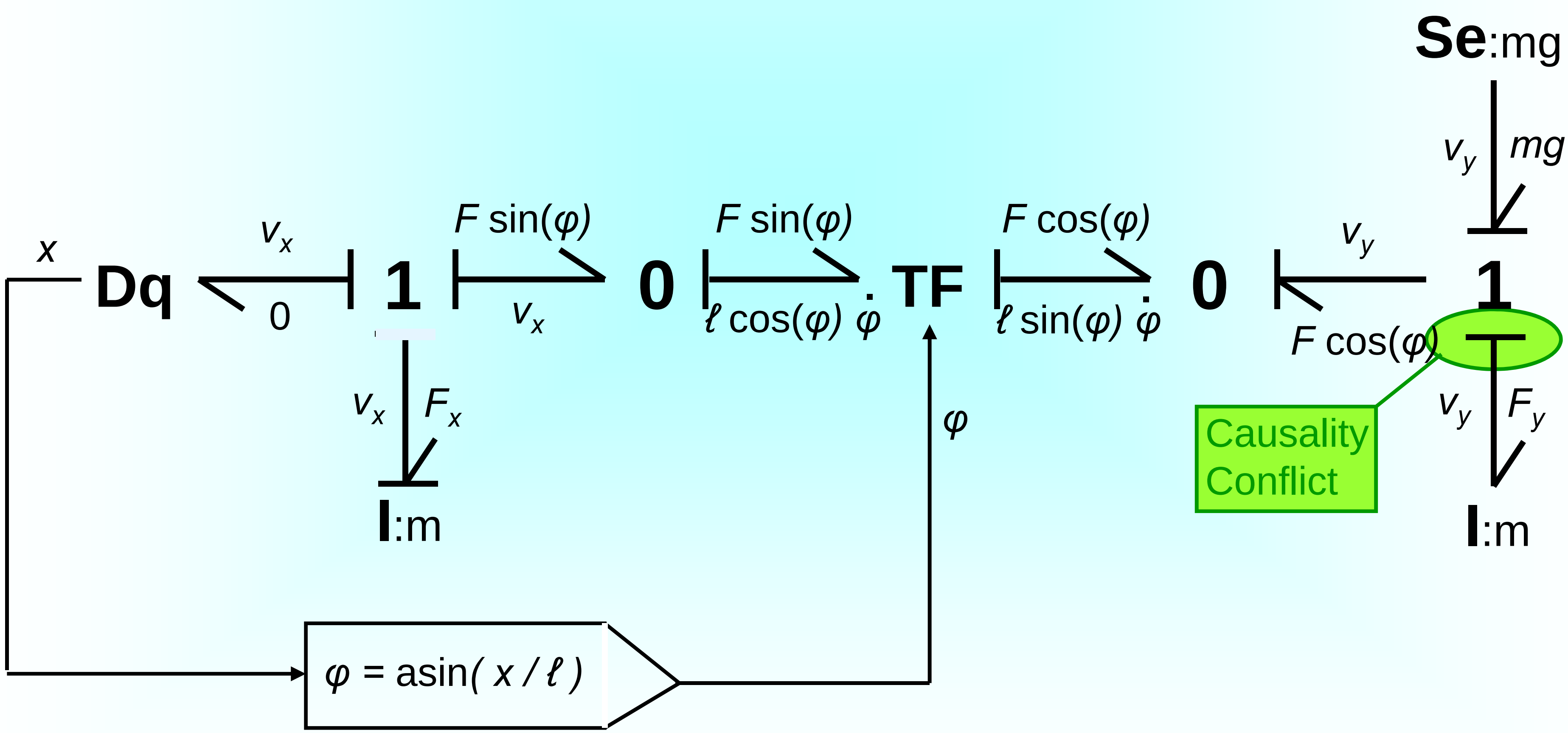
$$
\begin{aligned}
m \cdot \frac{dv_x}{dt} &= -\frac{F \cdot x}{\ell} \\
m \cdot \frac{dv_y}{dt} &= m \cdot g - \frac{F \cdot y}{\ell} \\
\frac{dx}{dt} &= v_x \\
\frac{dy}{dt} &= v_y \\
x &= \ell \cdot \sin(\varphi) \\
y &= \ell \cdot \cos(\varphi)
\end{aligned}
$$

$$m \frac{dv_x}{dt} = -F \sin(\varphi)$$

$$x = \ell \sin(\varphi)$$
$$v_x = \ell \cos(\varphi)\, \dot{\varphi}$$

$$y = \ell \cos(\varphi)$$
$$v_y = -\ell \sin(\varphi)\, \dot{\varphi}$$

$$m \frac{dv_y}{dt} = -F \cos(\varphi) + mg$$



Analysis

It has been possible to describe the motion of the planar pendulum by a bond graph enhanced by activated bonds for the description of the ***holonomic constraint***. Unfortunately, the bond graph doesn't tell us much that we didn't know already.

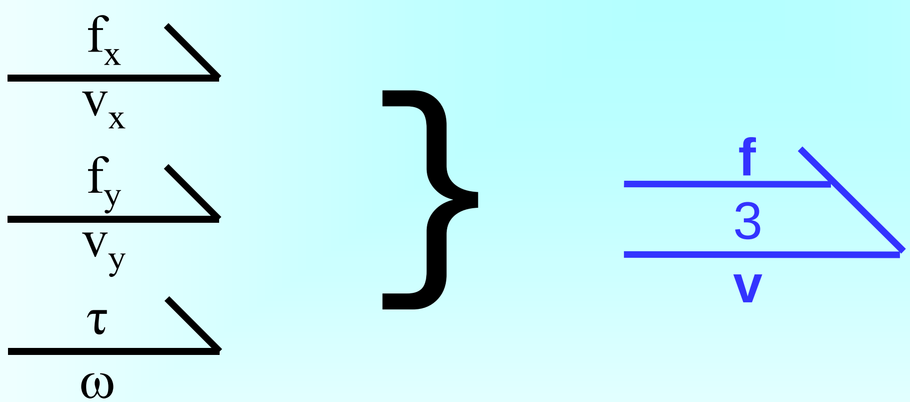
- We shouldn't have to derive the equations first in order to be able to derive the bond graph from them.

- The resulting bond graph didn't preserve the topological properties of the system in any recognizable form.

Multi-bonds

- Multi-bond graphs are a vector extension of the regular bond graphs.

- A multi-bond contains a freely selectable number of regular bonds of identical or similar domains.



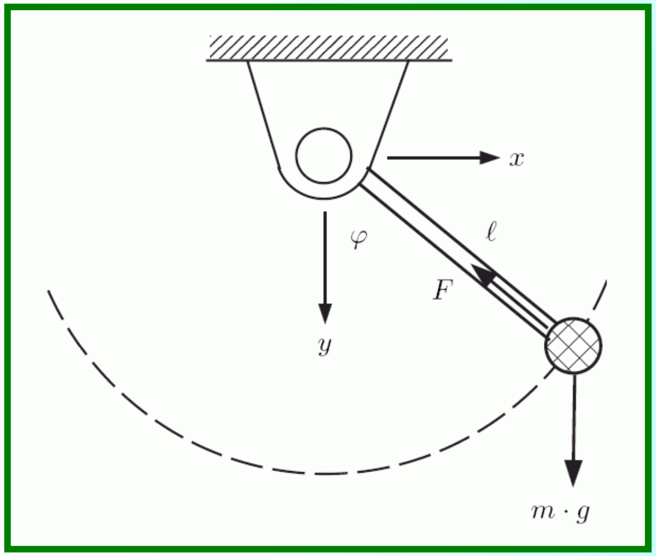
Composition of a multi-bond for planar mechanics

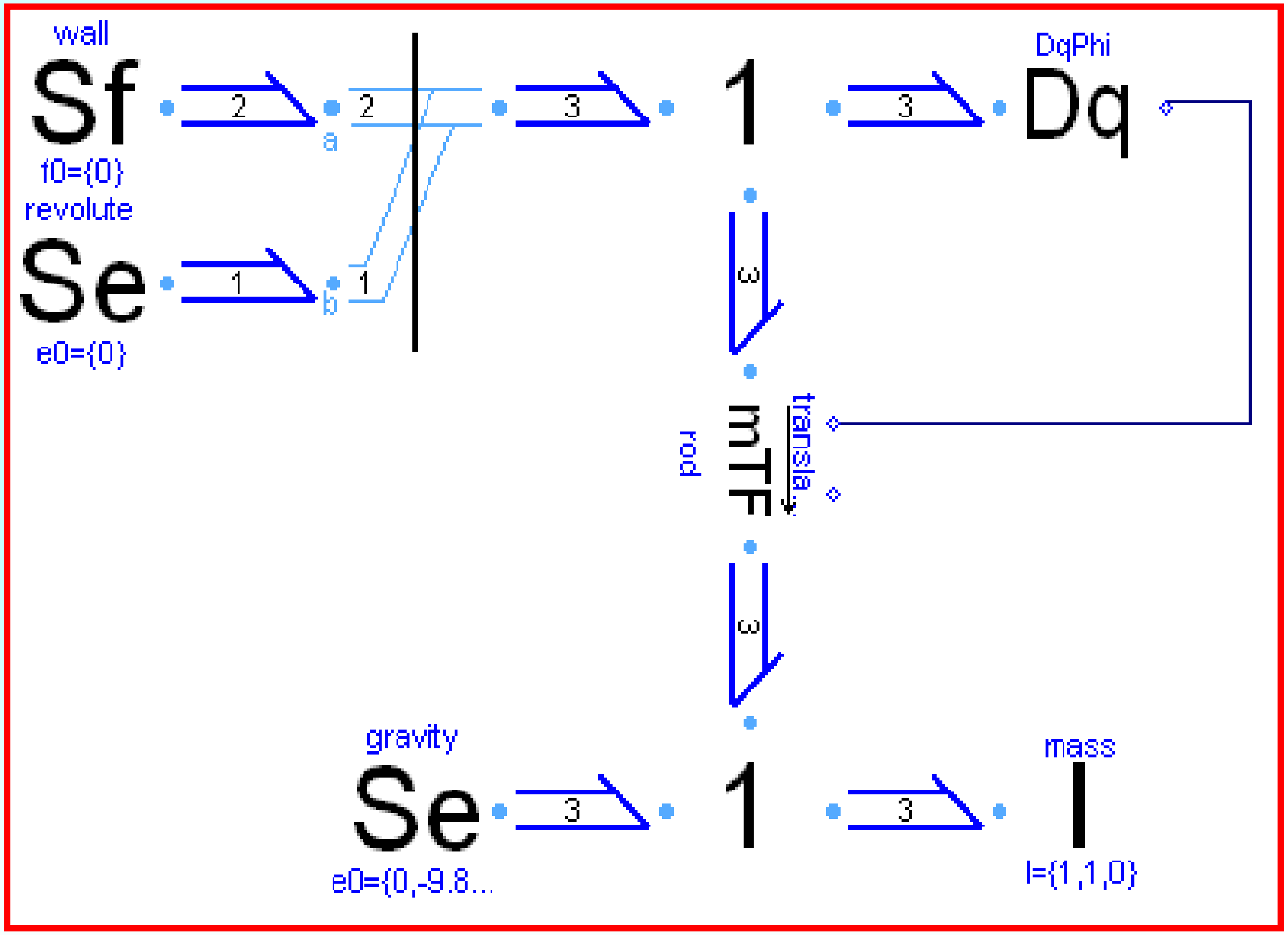
- All bond graph component models are adjusted in a suitable fashion.

Multi-bond Graph Library

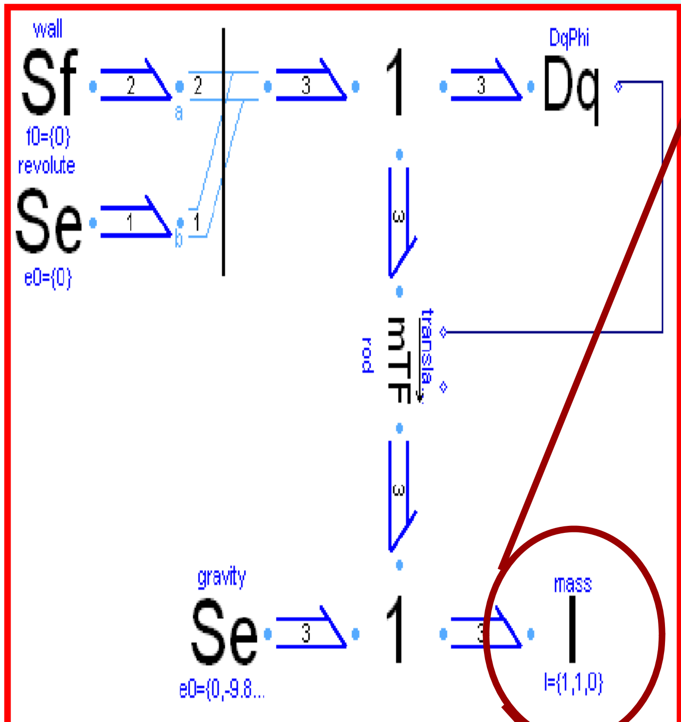
- A ***Dymola*** library for modeling systems by means of multi-bond graphs has been developed.
- The library has been designed with an interface that looks as much as possible like that of the original ***BondLib*** library.
- Just like the original library, also the new multi-bond graph library contains sub-libraries supporting modelers in modeling systems from particular application domains, especially from mechanics.

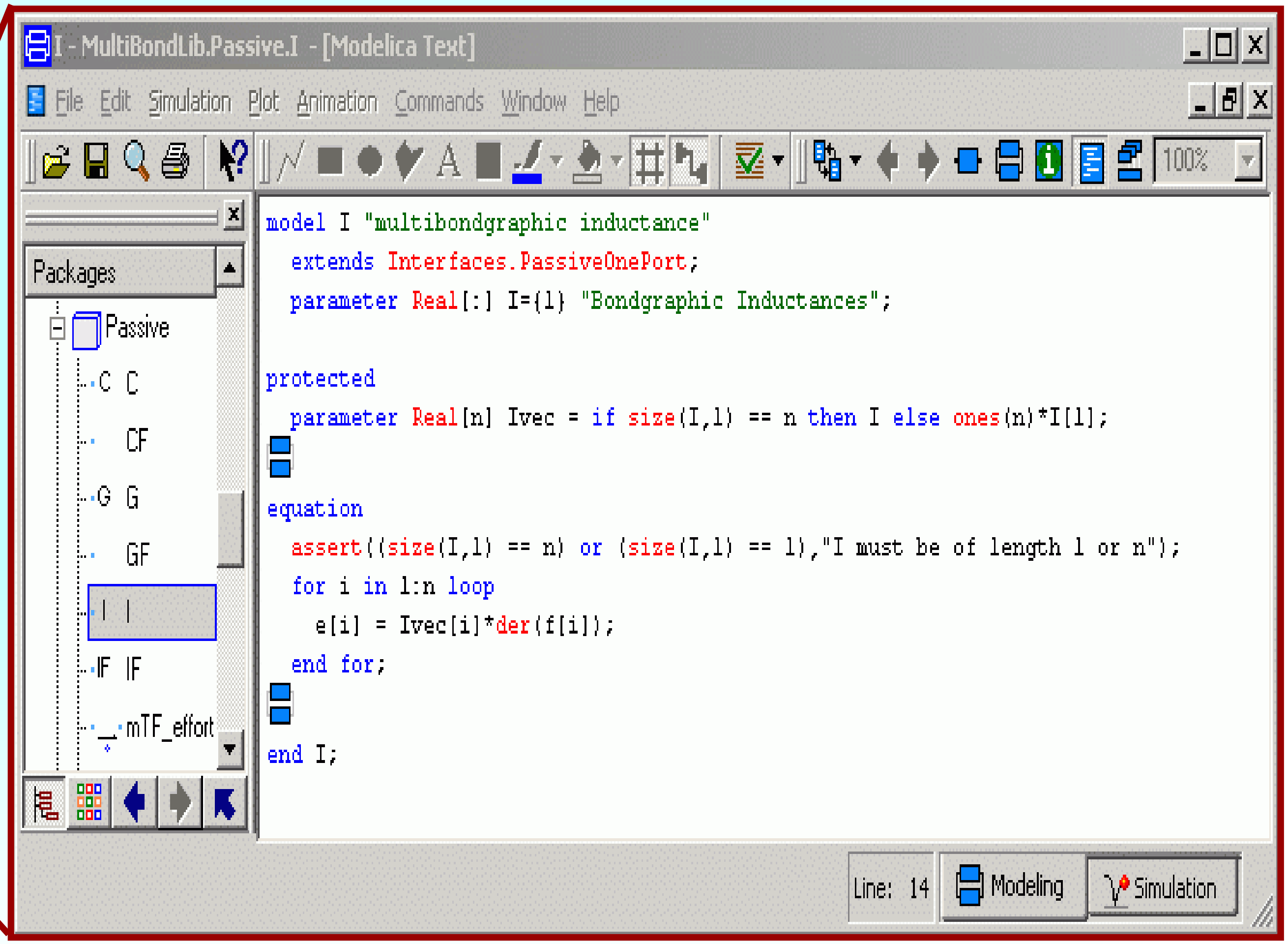
Planar Pendulum III



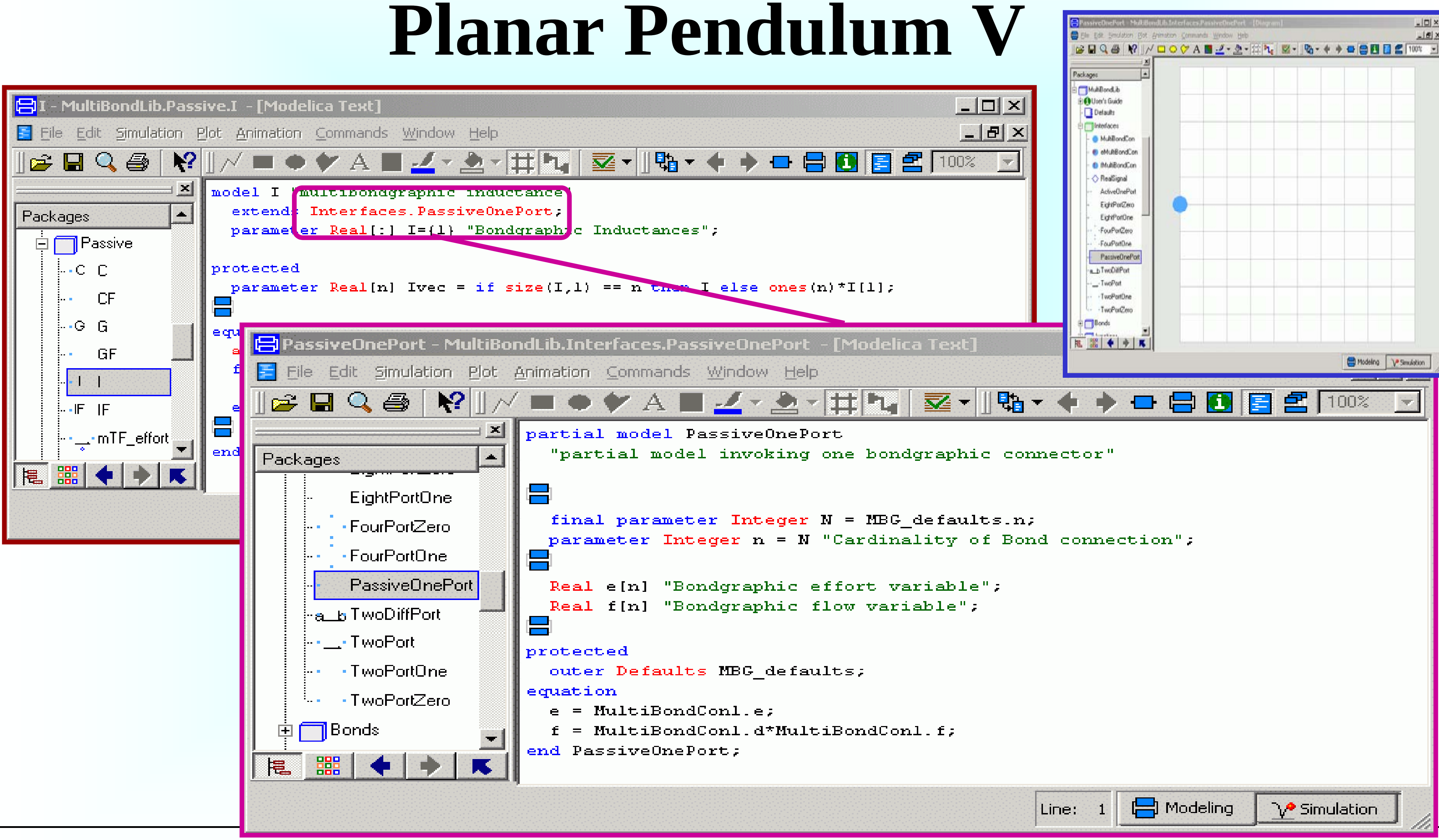


Planar Pendulum IV

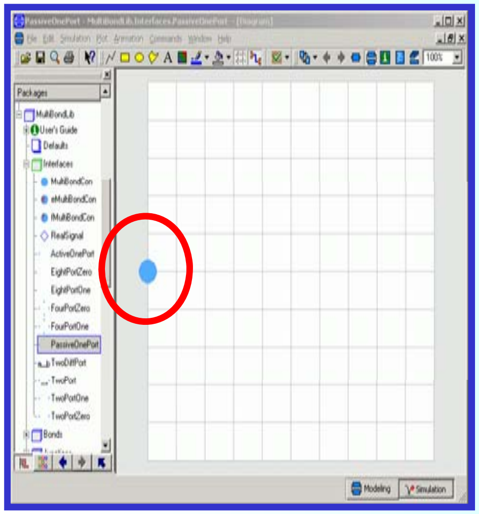


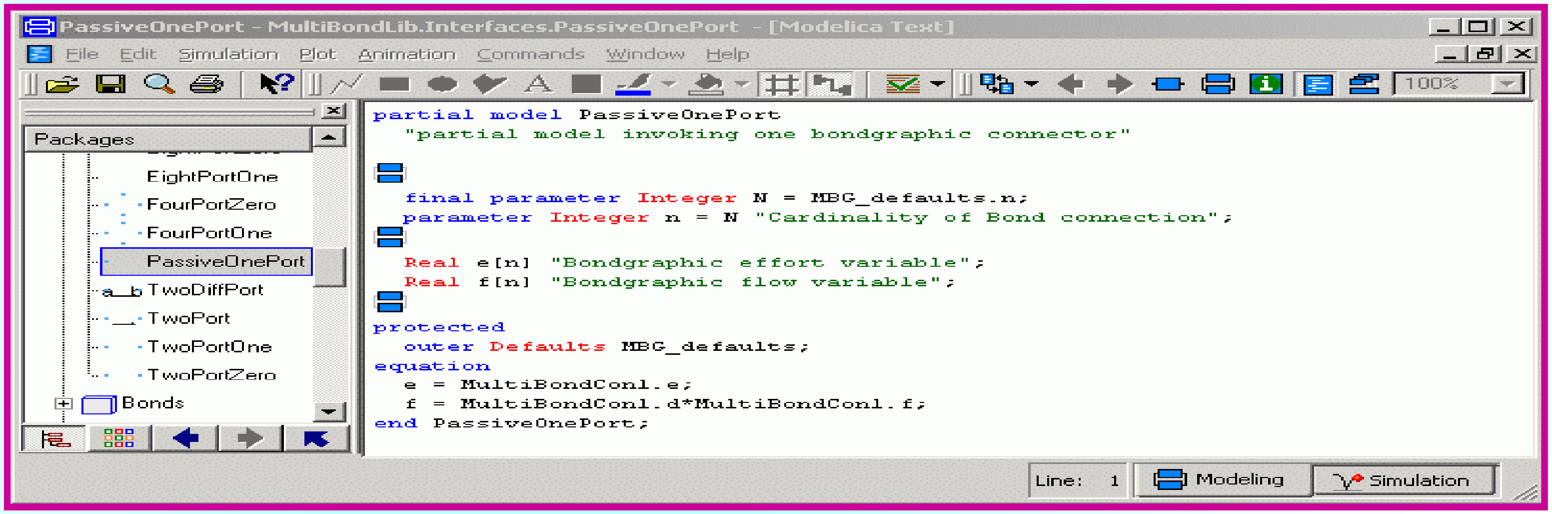


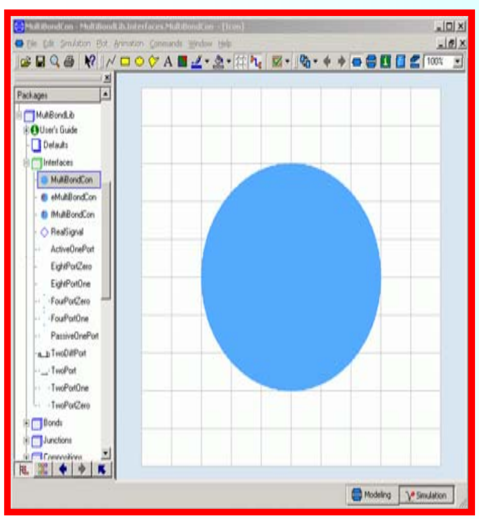
Planar Pendulum V

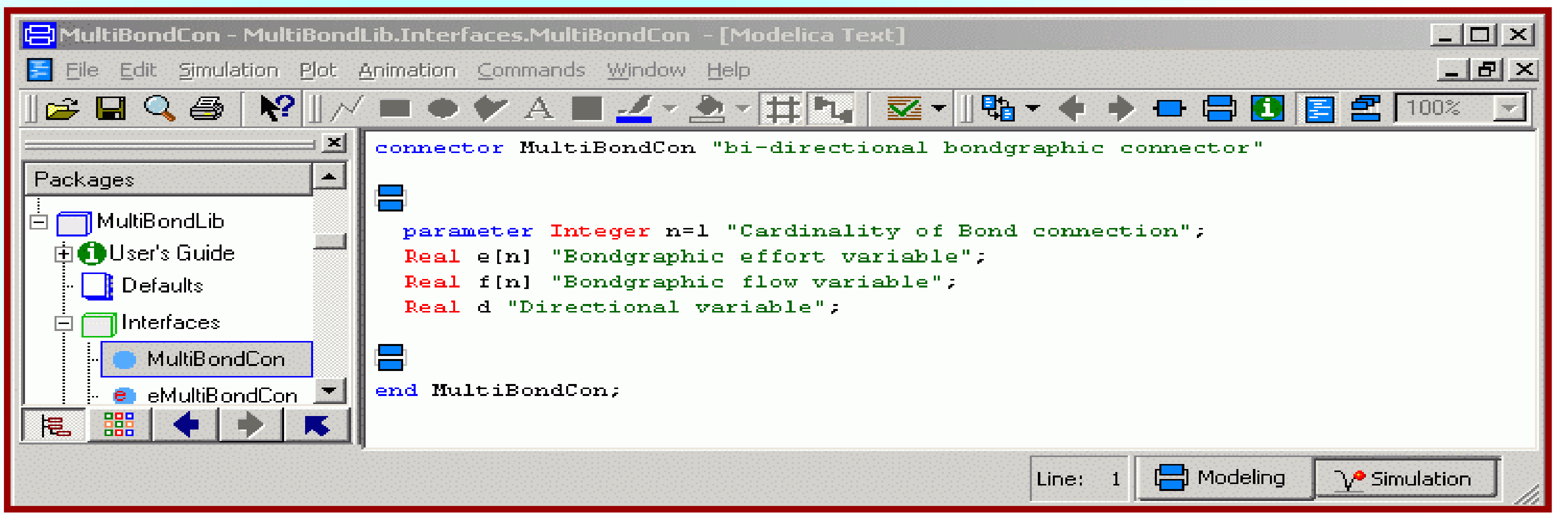


Planar Pendulum VI

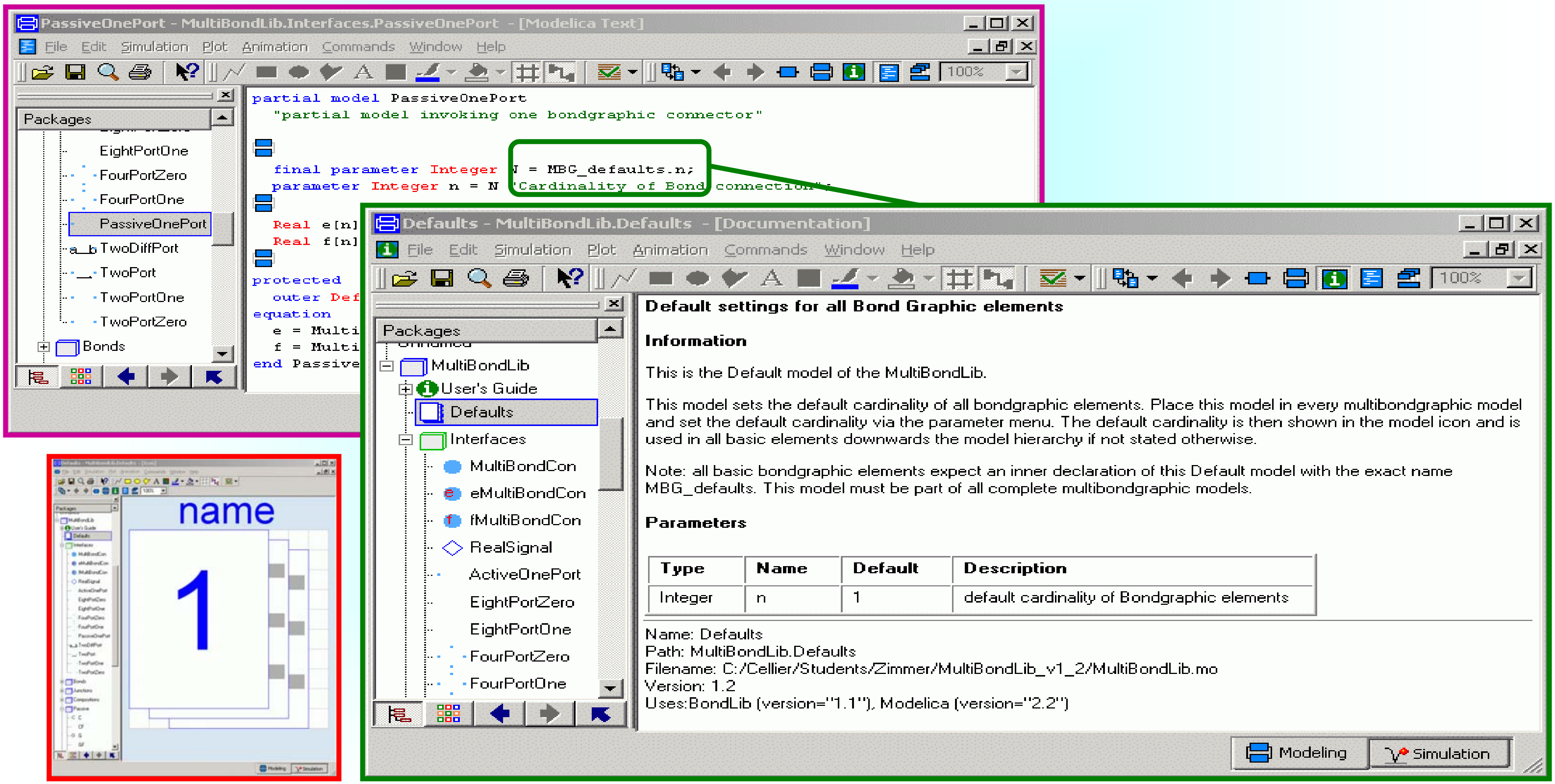




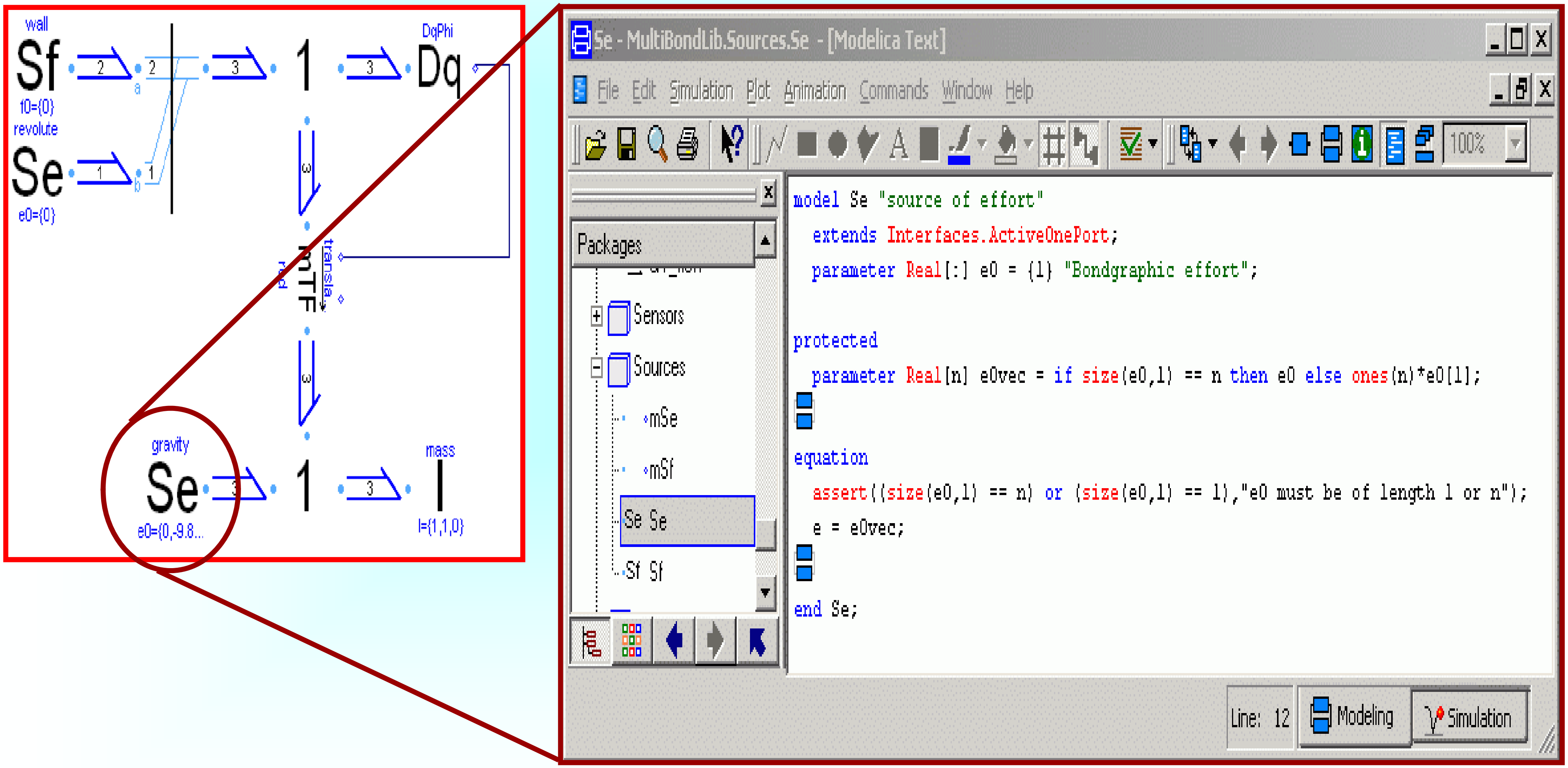




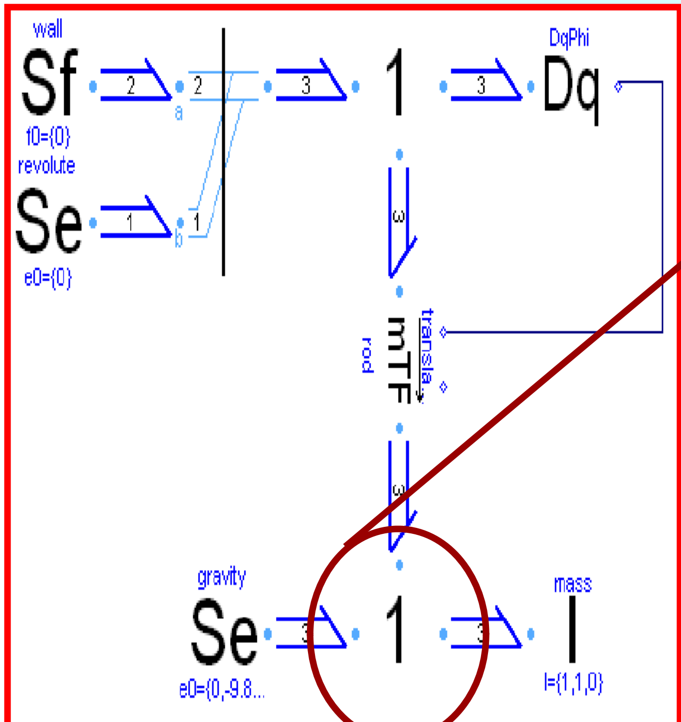
Planar Pendulum VII

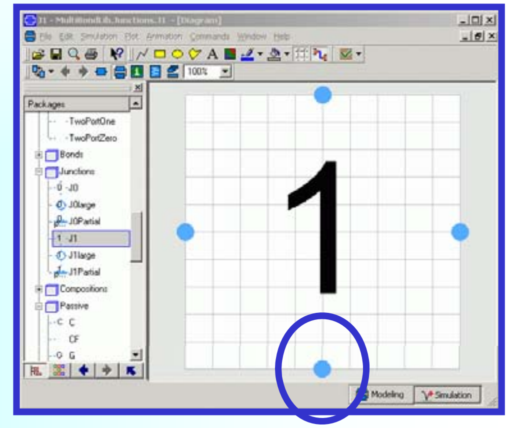


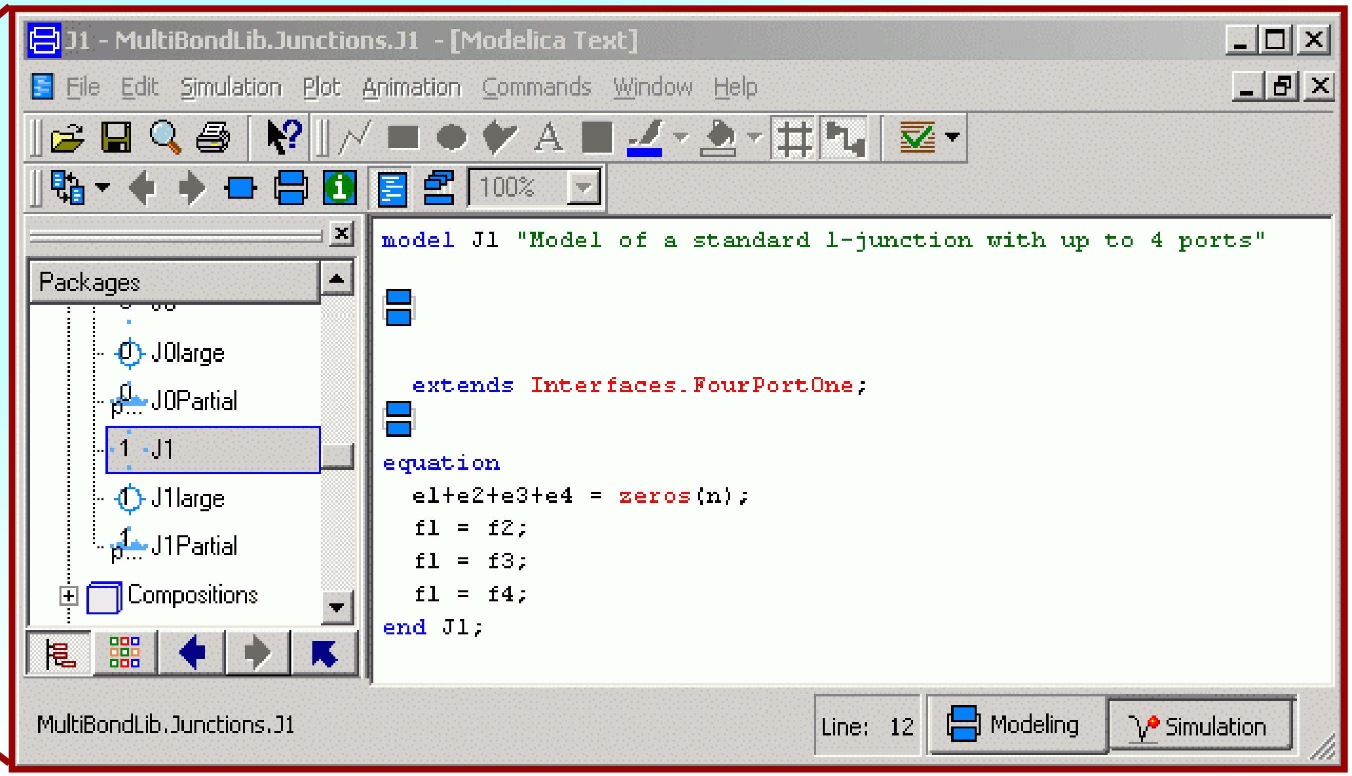
Planar Pendulum VIII



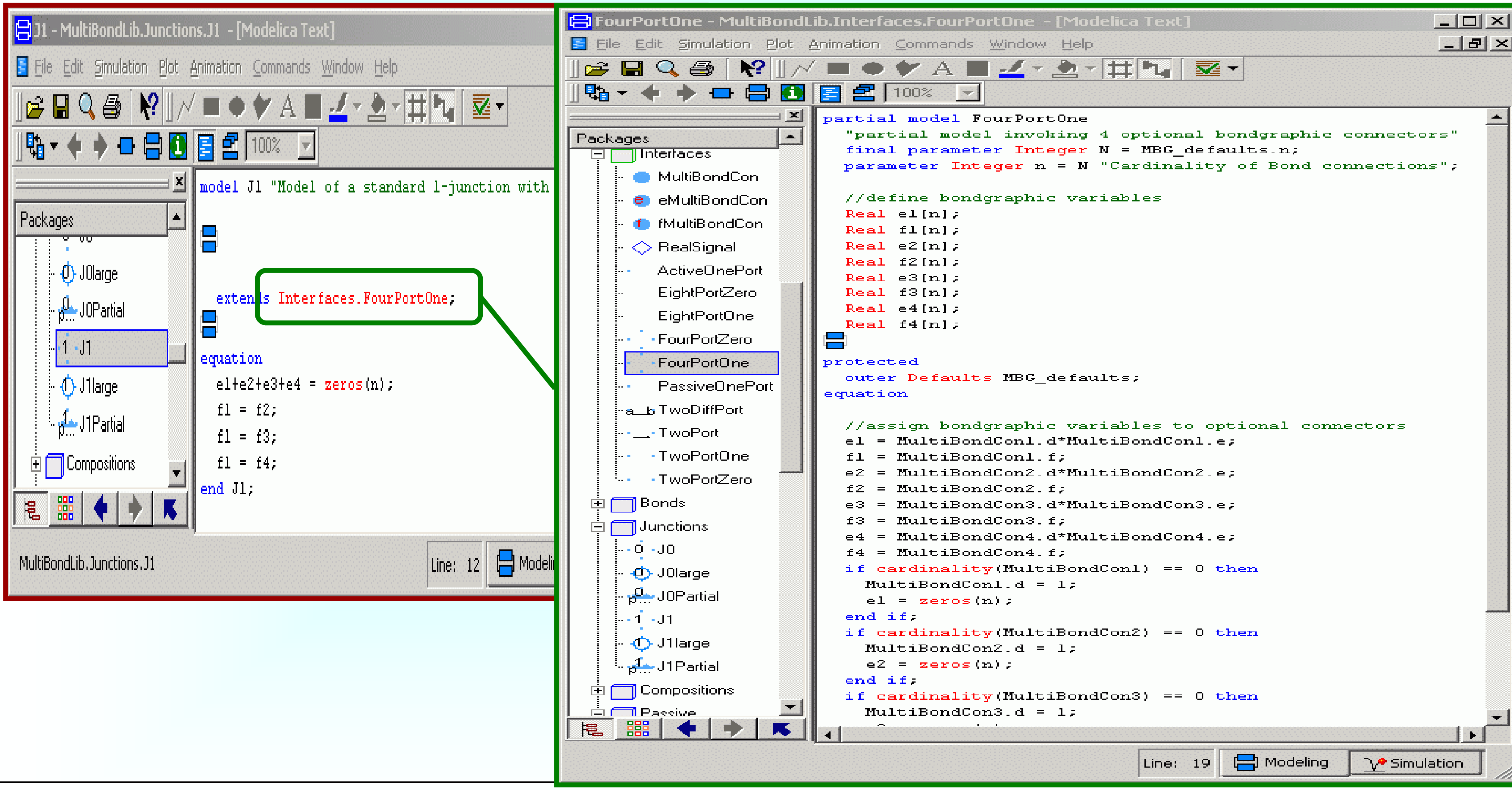
Planar Pendulum IX



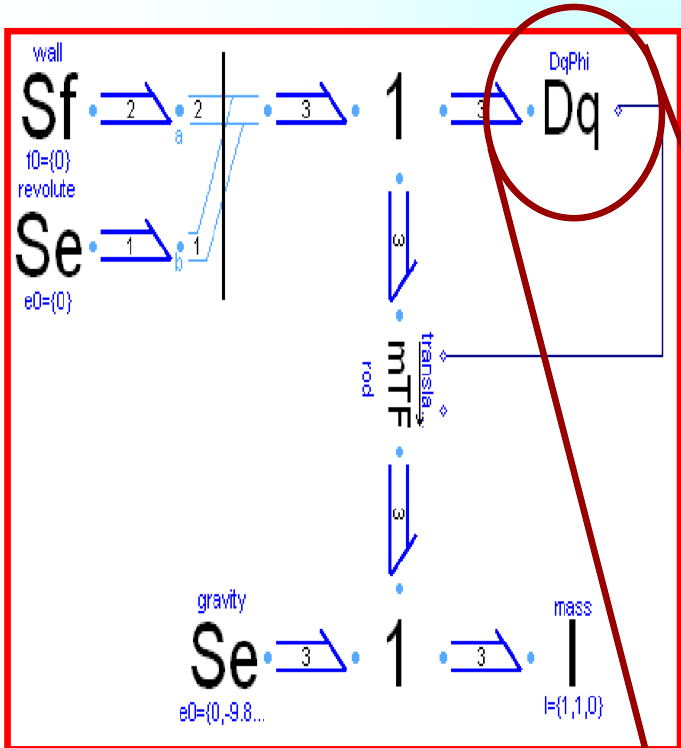




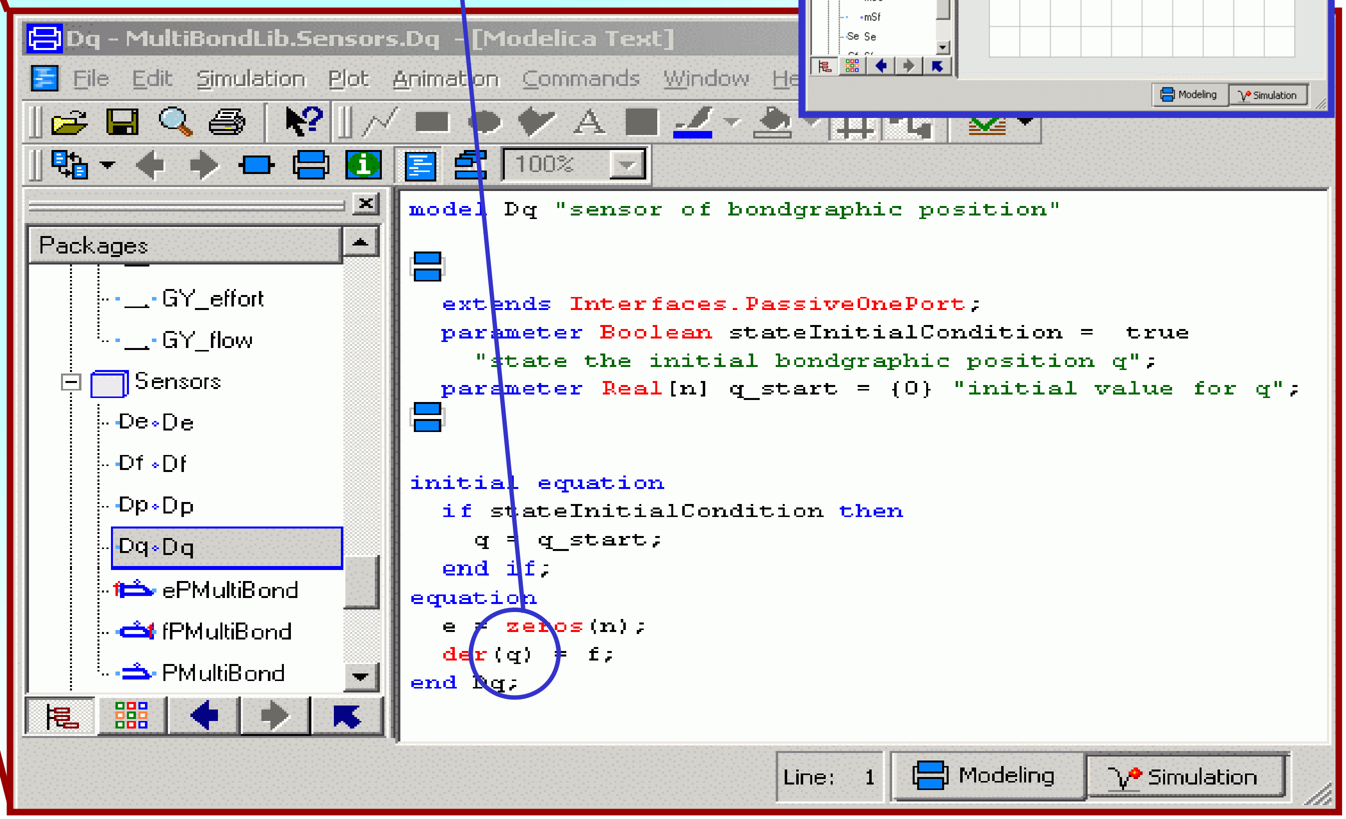
Planar Pendulum X

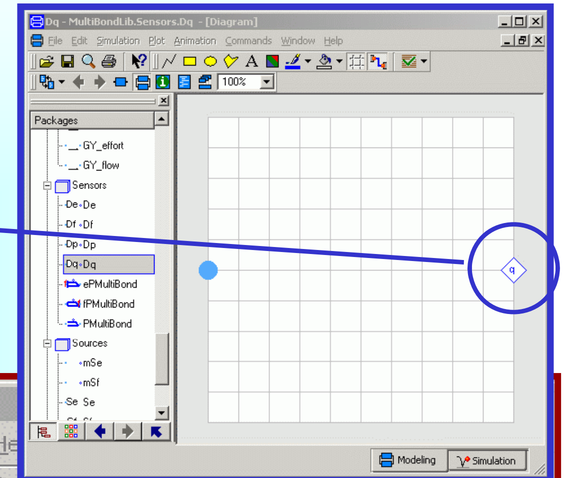


Planar Pendulum XI

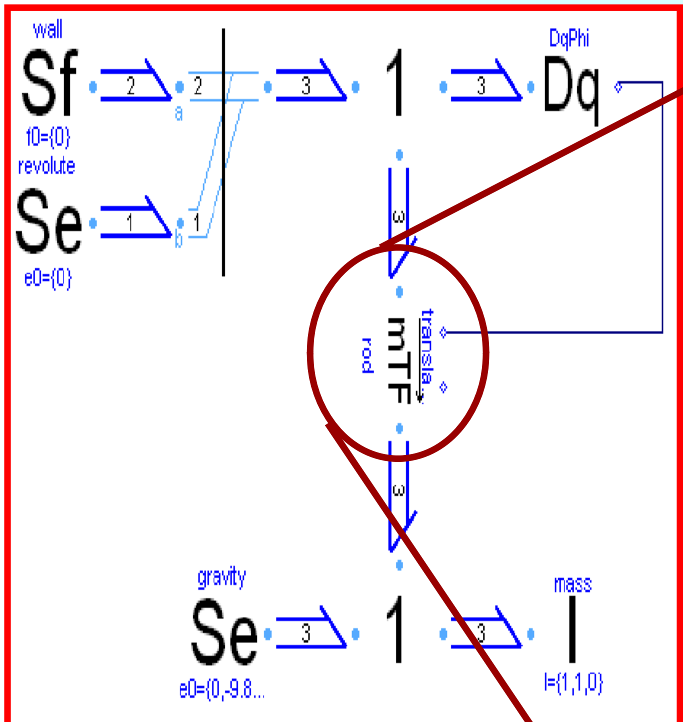


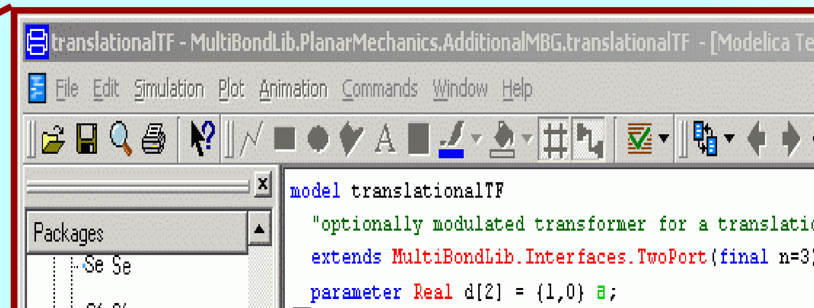
a-causal signal vector

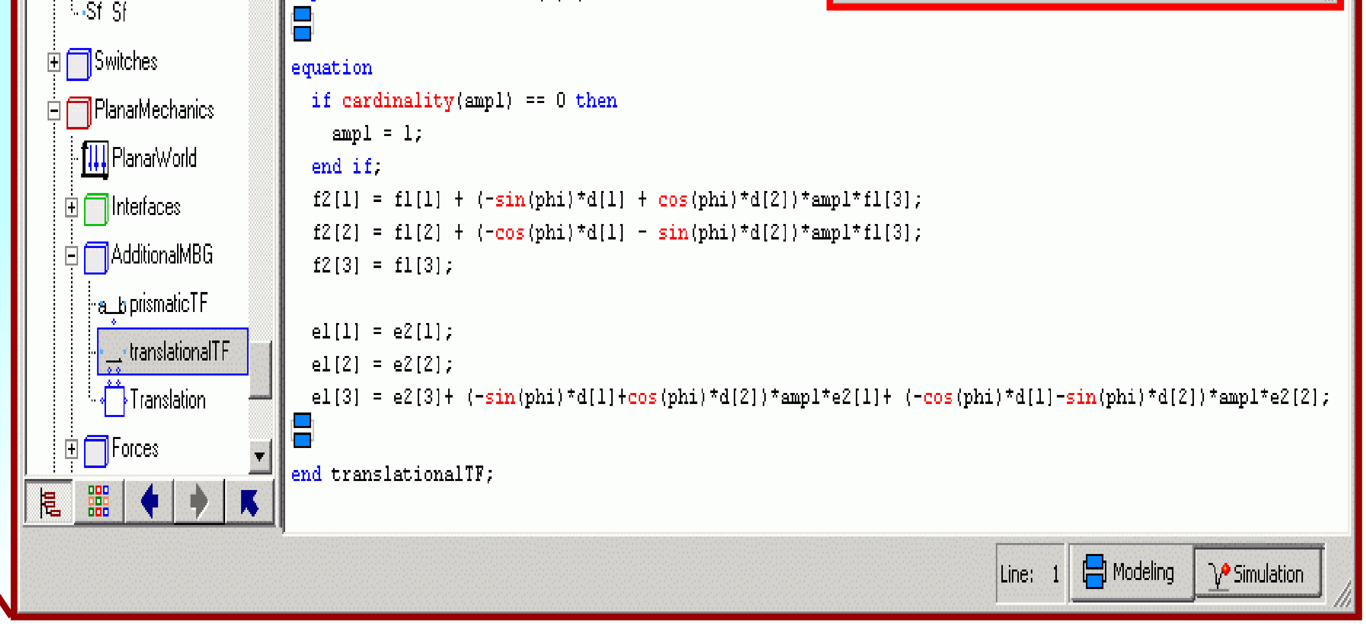


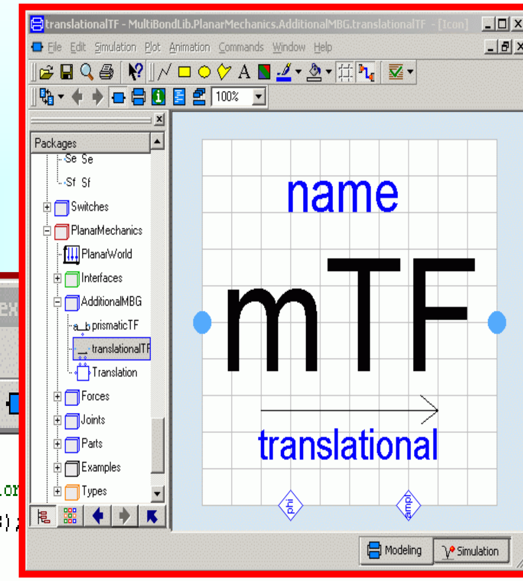


Planar Pendulum XII





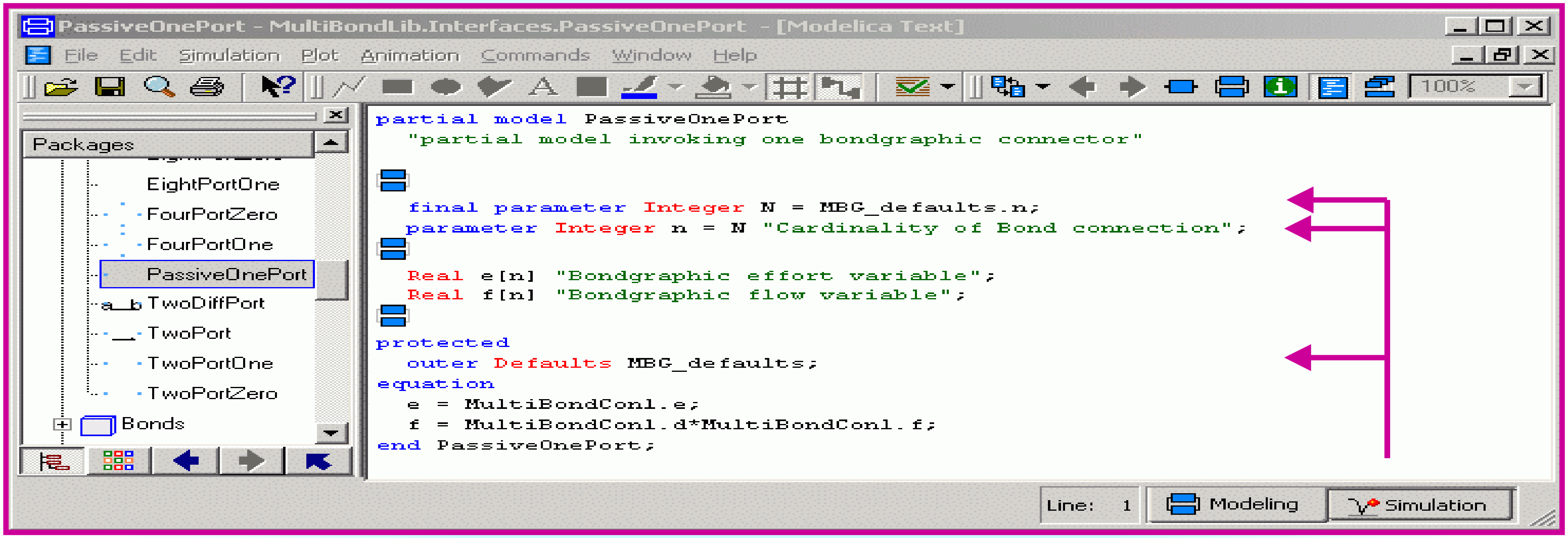




Multi-bond Graph Basics

- The basic multi-bond graph models contain little that is surprising. They represent essentially natural extensions of the regular bond graph models.
- A few points are worth mentioning though. First, there is the ***defaults model*** that must be included in each multi-bond graph model. It contains only a single parameter, the dimensional parameter, ***n***, that specifies, how many bonds each multi-bond contains by default.
- The defaults model must be referenced in each multi-bond graph model as an ***outer model***.

Multi-bond Graph Basics II



- If the multi-bond graph model inherits one of the partial models, this has already been taken care of.

Multi-bond Graph Basics III

- A second difference concerns the use of junctions. Whereas the general bond graph library provides separate junction models for 2..6 bond connections, the multi-bond graph library offers only junctions with either 4 or 8 connectors. Yet, individual connectors may be left unconnected as needed.
- A third difference is in the use of transformers and gyrators. The multi-bond graph library offers a much larger variety of different transformer and gyrator models when compared to the regular bond graph library.

Multi-port Transformers

$$\overset{\underline{e}_1}{\underset{\underline{f}_1}{\rightharpoonup}}\ \underset{\mathbf{M}}{\mathbf{TF}}\ \overset{\underline{e}_2}{\underset{\underline{f}_2}{\rightharpoonup}}$$

Transformation: $\underline{e}_1 = M \cdot \underline{e}_2$ **(1)**

Energy Conservation: $\underline{e}_1^T \cdot \underline{f}_1 = \underline{e}_2^T \cdot \underline{f}_2$ **(2)**

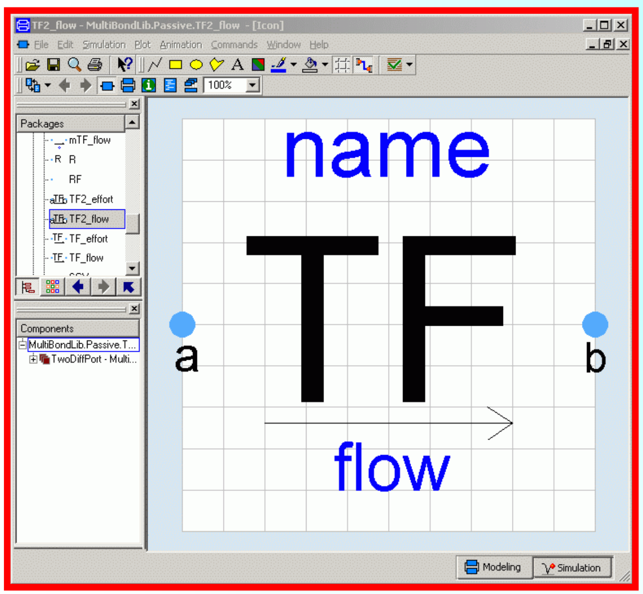
$\Rightarrow \quad (M \cdot \underline{e}_2)^T \cdot \underline{f}_1 = \underline{e}_2^T \cdot \underline{f}_2$ **(3)**

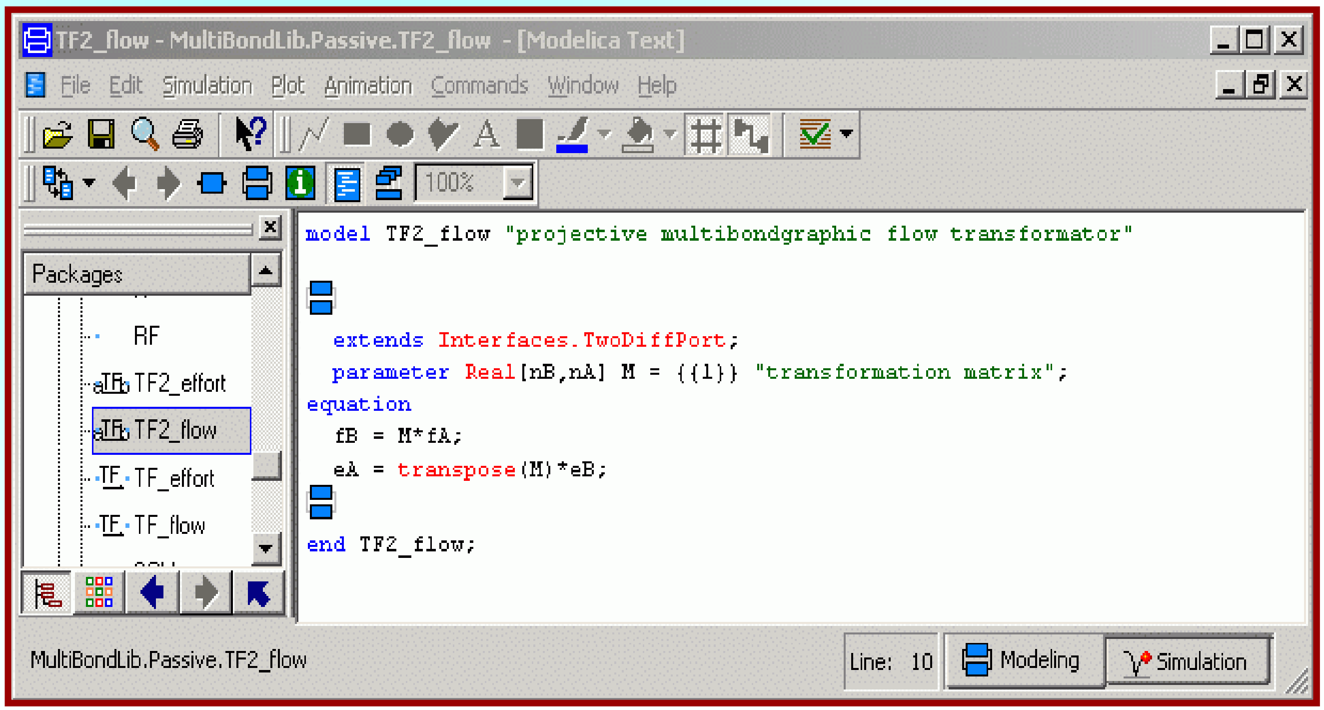
$\Rightarrow \quad \underline{f}_2 = M^T \cdot \underline{f}_1$ **(4)**

$\Rightarrow$ ***The transformer may either be described by means of equations (1) and (2) or using equations (1) and (4).***

Multi-port Transformers II

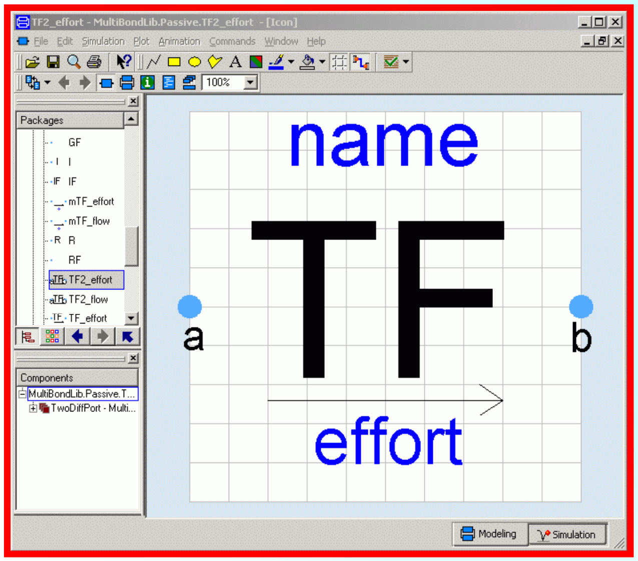
- The transformer that looks most similar to the TF element of the regular bond graph library is the flow multi-port transformer. The cardinality of the bonds on the two sides doesn't have to be identical.

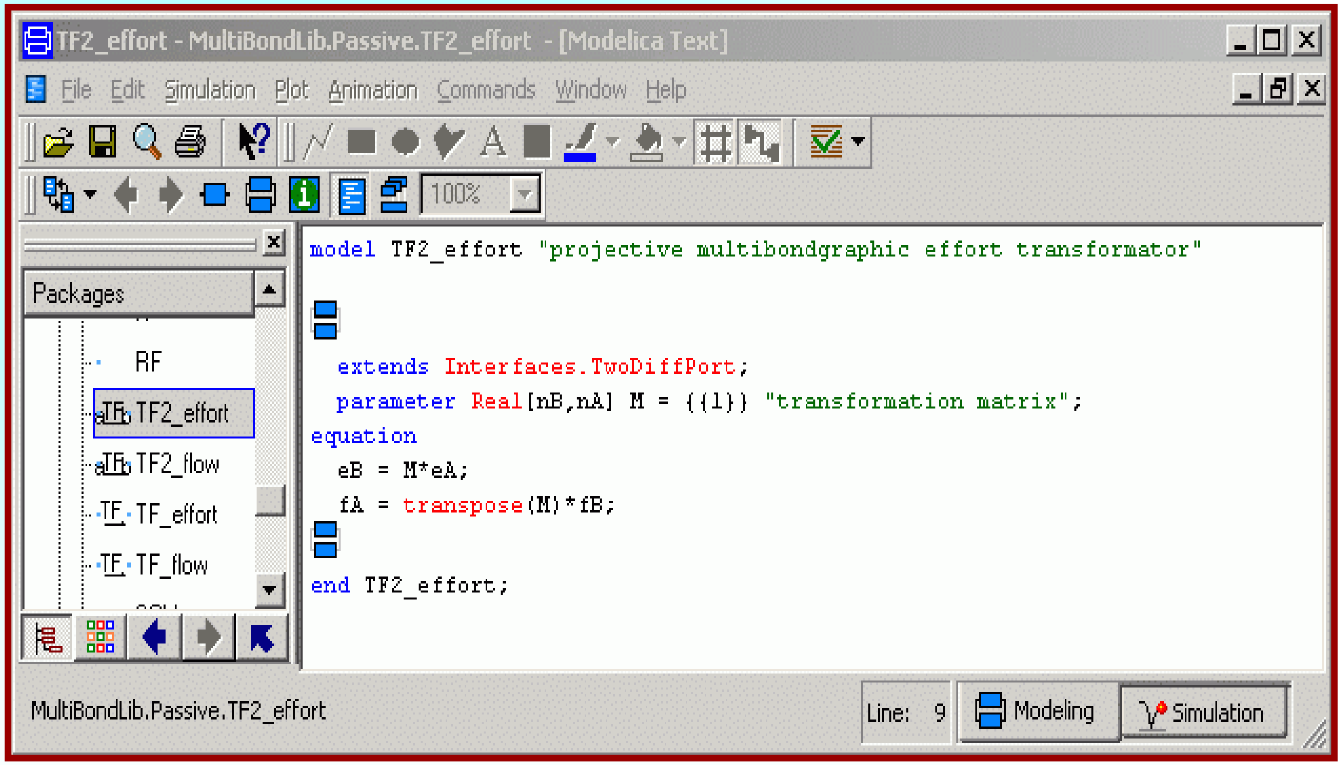




Multi-port Transformers III

- Yet, since ***M*** doesn't usually have an inverse, an effort transformer model must also be provided.

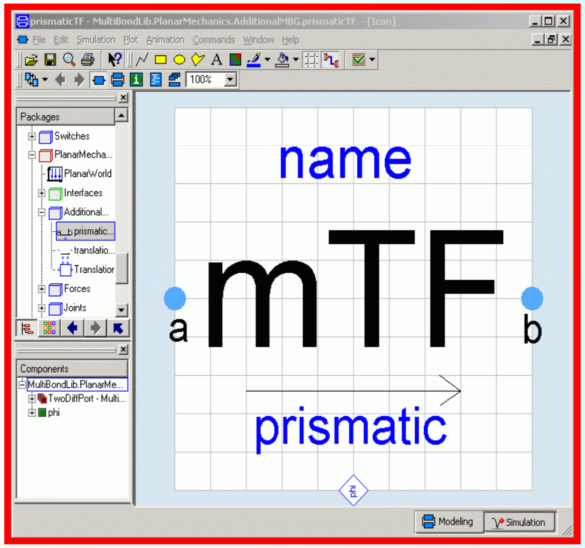


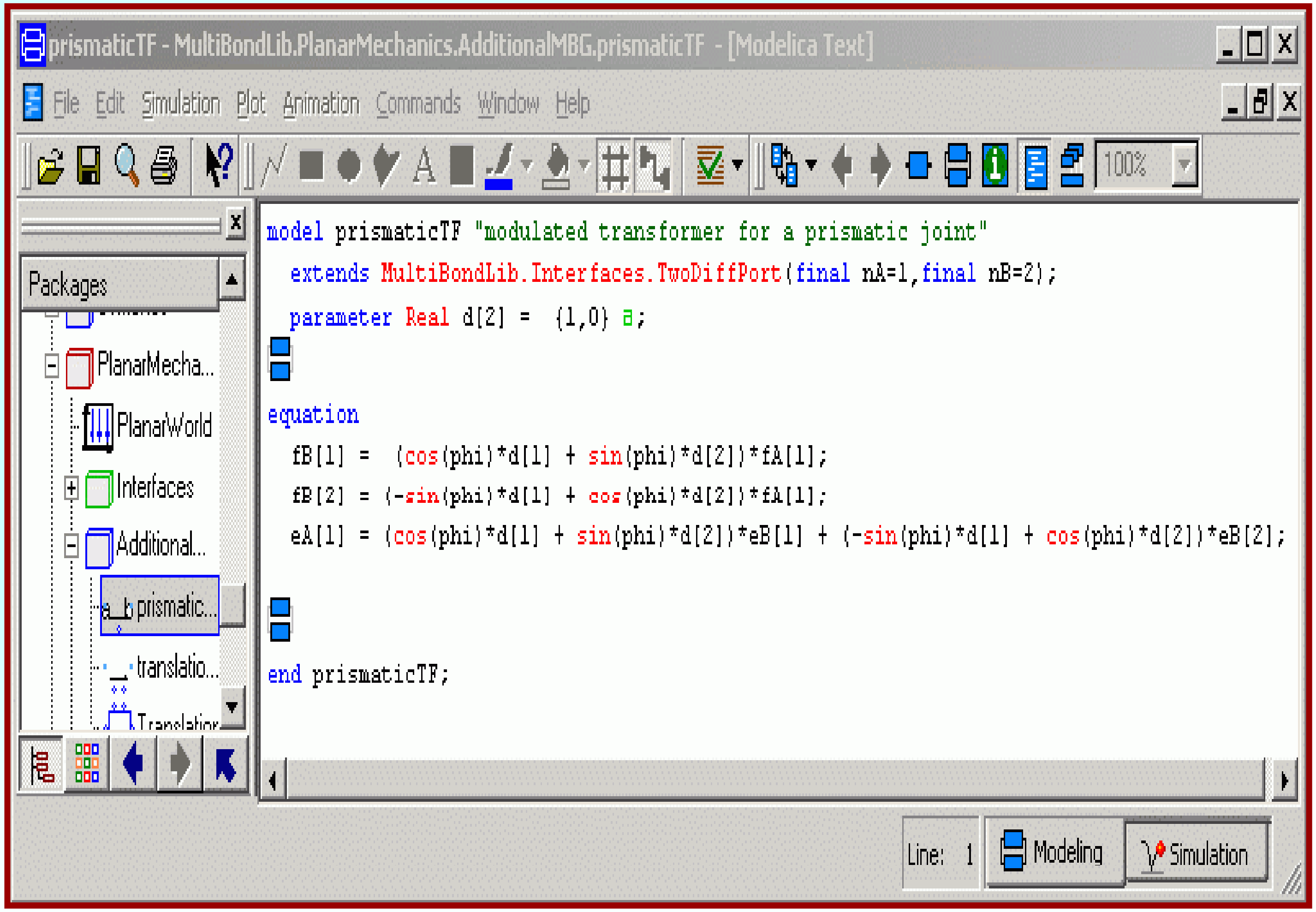


Multi-port Transformers IV

- Also offered are modulated versions of multi-port transformers and gyrators.
- Yet, this is still insufficient. Special transformers for particular purposes ought to be provided as well, since they are being used frequently in mechanics.
- We already met the ***translational transformer***.
- Also provided is a ***prismatic transformer***.
- The special transformers are contained in the 2D mechanics sub-library, since they are only useful in that context.

Multi-port Transformers V

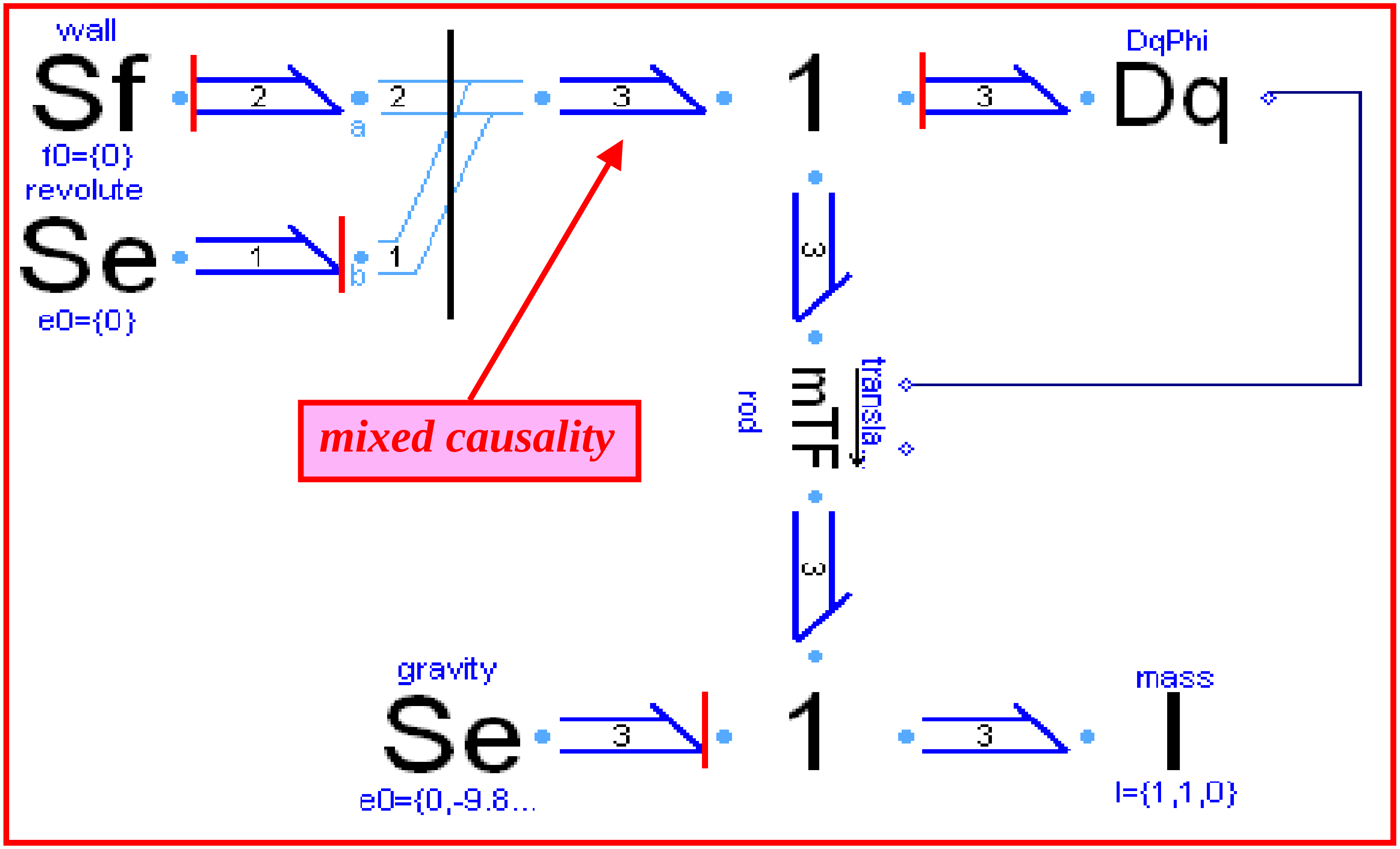




Multi-bond Graph Basics IV

- Finally, although the library offers causal multi-bonds, these are much less useful than the causal regular bonds, because many multi-bonds have mixed computational causality. Hence causal multi-bonds are rarely used in practice.

Planar Pendulum XIII



References I

- Zimmer, D. (2006), *A Modelica Library for MultiBond Graphs and its Application in 3D-Mechanics*, MS Thesis, Dept. of Computer Science, ETH Zurich.

- Zimmer, D. and F.E. Cellier (2006), "The Modelica Multi-bond Graph Library," *Proc. 5th Intl. Modelica Conference*, Vienna, Austria, Vol.2, pp. 559-568.

References II

- Cellier, F.E. and D. Zimmer (2006), "Wrapping Multi-bond Graphs: A Structured Approach to Modeling Complex Multi-body Dynamics," *Proc. 20th European Conference on Modeling and Simulation*, Bonn, Germany, pp. 7-13.