

Numerical Simulation of Dynamic Systems XXIII

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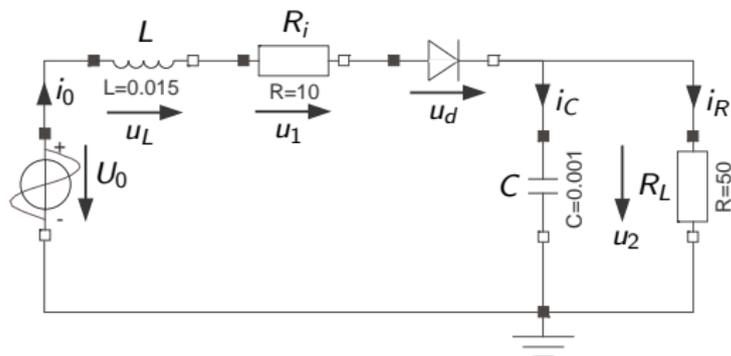
May 14, 2013

Variable Structure Models

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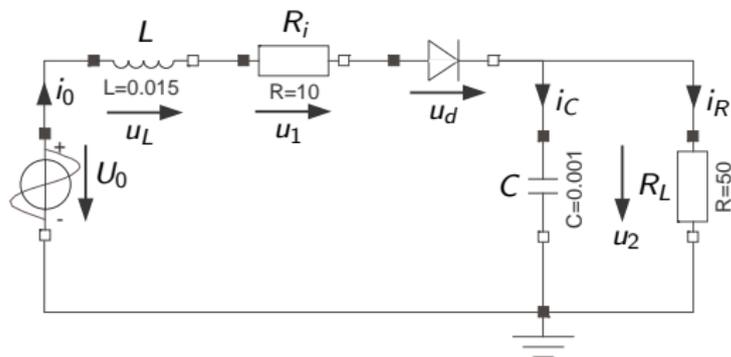
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$$u_2 = R_L \cdot i_R$$

$$i_C = C \cdot \frac{du_2}{dt}$$

$$u_L = L \cdot \frac{di_0}{dt}$$

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$$i_0 = i_C + i_R$$

$$u_d = m_o \cdot s$$

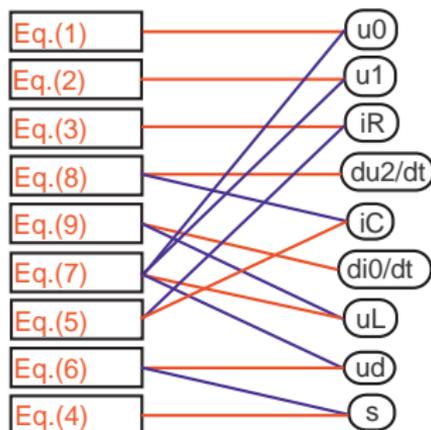
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$$u_L = u_0 - u_1 - u_d - u_2$$

$$\frac{du_2}{dt} = \frac{1}{C} \cdot i_C$$

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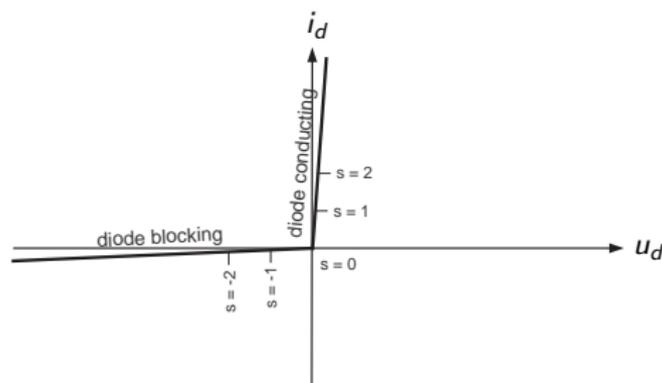
- ▶ When we try to simulate this model, we get a division by zero as soon as the switch opens for the first time.
- ▶ The reason is simple: we failed to include the switch equation inside an algebraic loop. Thus, the causality on the switch was fixed, which invariably leads to a division by zero in one of the two switch positions.
- ▶ The cause of the problem is quite obvious. The inductor defines the inductive current as a state variable, i.e., i_0 is a known variable. Since this current flows also through the diode, we have no choice but to always compute the voltage across the diode, u_d , from the diode characteristic. Hence the causality of the diode is fixed, which foretells disaster.

Variable Structure Models IV

The **Modelica Standard Library** tackles this problem by replacing the *ideal diode* by a *leaky diode*:

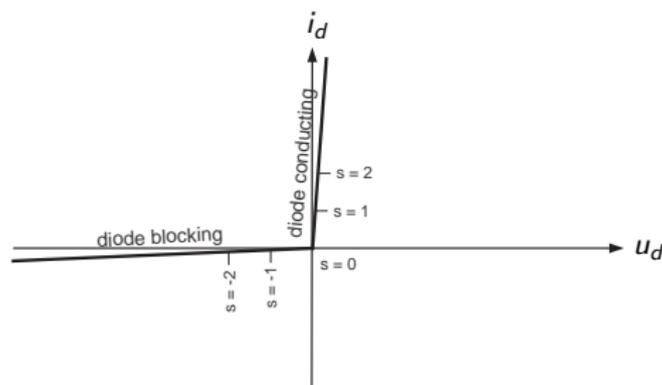
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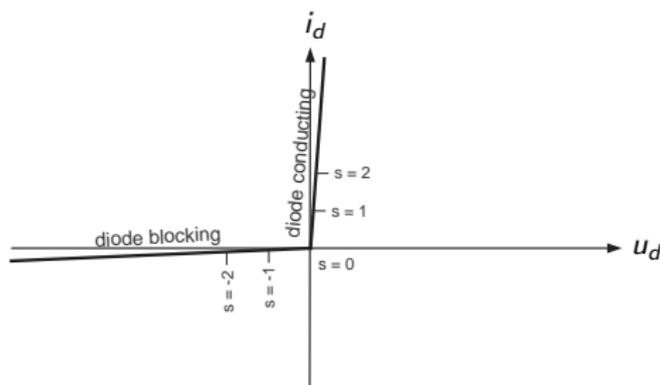


Logical model equations:

$$\begin{aligned}
 u_d &= \text{if } \text{OpenSwitch} \text{ then } s \text{ else } R_0 \cdot s; \\
 i_d &= \text{if } \text{OpenSwitch} \text{ then } G_0 \cdot s \text{ else } s; \\
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Algebraic model equations:

$$\begin{aligned}
 u_d &= [m_o + (1 - m_o) \cdot R_0] \cdot s; \\
 i_d &= [m_o \cdot G_0 + (1 - m_o)] \cdot s; \\
 m_o &= \text{if } s < 0 \text{ then } 1 \text{ else } 0;
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The leaky diode model doesn't change the causalities of the equation system, i.e., the structure digraph of the model using the leaky diode is exactly the same as that using the ideal diode. However, the leaky diode avoids the division by zero.

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The causal equations of the model using the leaky diode are:

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$$s = \frac{1}{m_o \cdot G_0 + (1 - m_o)} \cdot i_0$$

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- ▶ Furthermore, the simulation results often depend significantly on the value of these non-physical fudge parameters.
- ▶ For these reasons, we would prefer to use an *ideal diode model* if we could.

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- ▶ Variable structure systems are very common, e.g. in mechanical engineering. All systems involving clutches are by their very nature variable structure systems. In electrical engineering, most switching power converters are variable structure systems.
- ▶ The way, the equations of our system were formulated, it doesn't look like these equations contain a *structural singularity*. There is no constraint equation to be found. The singularity looks to be *parametric* in nature, thus the *Pantelides algorithm* cannot solve it.

Mixed-mode Integration

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By now, the current, i_0 , is algebraic and linear in the voltage, u_L , i.e., **the causality of the inlined inductor is free.**

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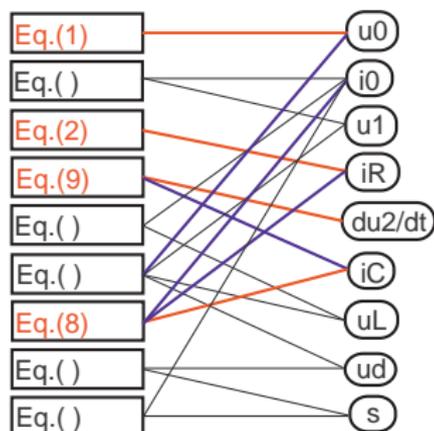
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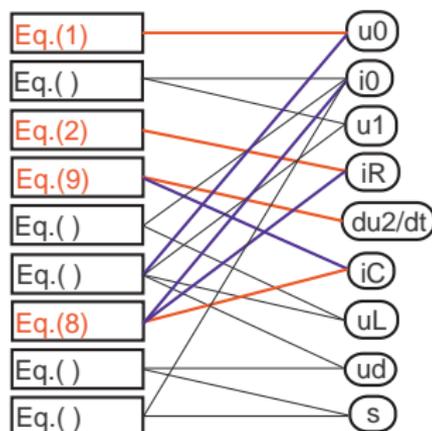
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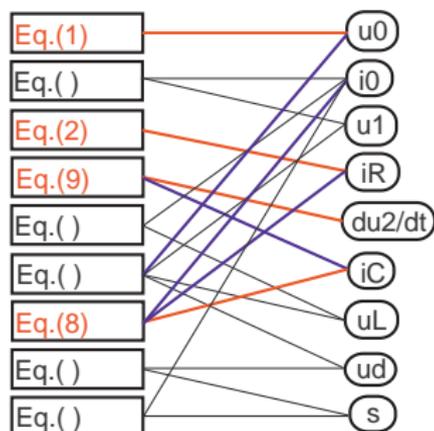
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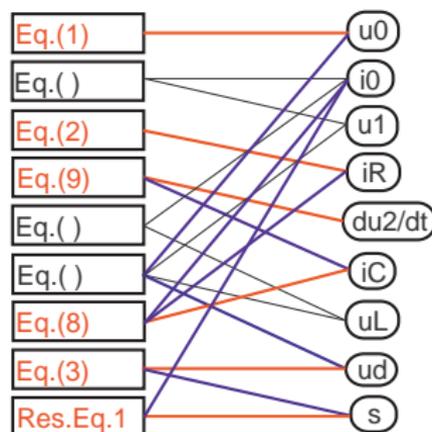
We encounter an algebraic loop in five equations and five unknowns.

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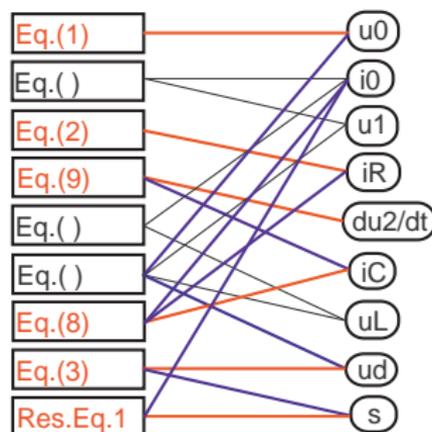
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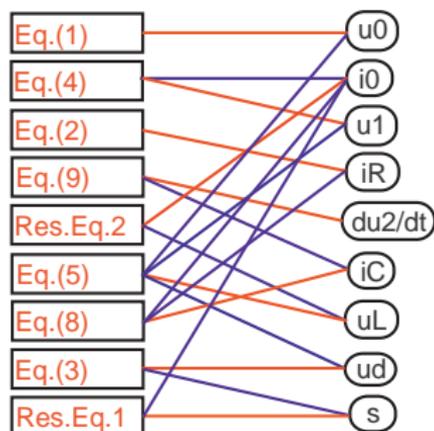
Unfortunately, there is still a second embedded algebraic loop in three equations and three unknowns.

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We choose a second residual equation and complete the causalization:

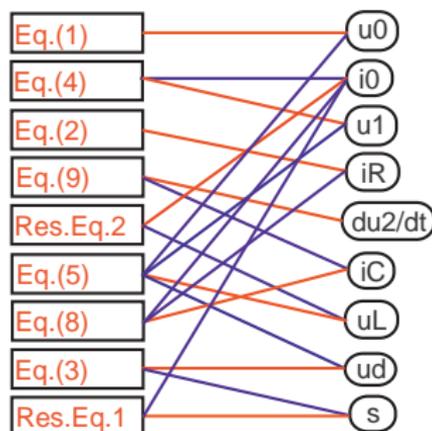
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$$s = \frac{L \cdot \text{pre}(i_0) + h \cdot (u_0 - u_2)}{h \cdot m_o + (L + h \cdot R_i) \cdot (1 - m_o)}$$

$$u_d = m_o \cdot s$$

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- ▶ There is no stiffness problem in the model.
- ▶ The switch variable m_0 is still a discrete state variable that must be initialized in the initialization section of the model.

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- ▶ When the switch is closed, we are dealing with an *index-0 model*.
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- ▶ However, we mentioned that it is better to perform index reduction first, e.g. using the Pantelides algorithm.
- ▶ Unfortunately, the Pantelides algorithm usually doesn't work when dealing with conditional index changes.

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- ▶ When the clutch is locked, the two bodies move together, causing a constraint among the rotational positions of the two bodies. Thus, we are now dealing with an *index-3 model*.

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- ▶ In this situation, mixed-mode integration will probably not be able to save our neck.

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- ▶ Once the new causalization has been obtained, the simulation is resumed, interpolating between the final values of the previous simulation segment to obtain the initial conditions of the new segment. Since the set of state variables has changed, we need to determine new initial conditions from the information available just prior to the structure change.

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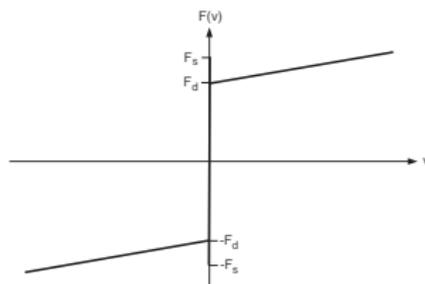
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- ▶ The Mosilab model compiler uses *static causalization*, but generates separate simulation models for all combinations of switches at compile time, together with conditions of when to change from one set of simulation equations to another.
- ▶ Unfortunately, the Mosilab approach doesn't scale well, because the number of simulation models grows exponentially with the number of switches, and because the set of initial conditions of each of these models grows quadratically in the number of simulation models.

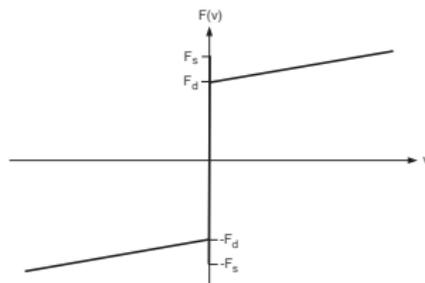
Mechanical Friction

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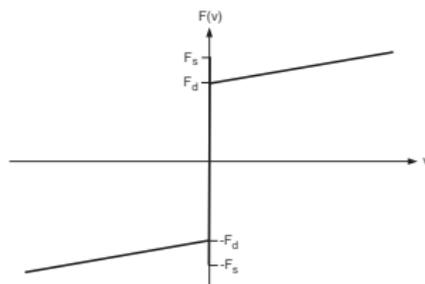
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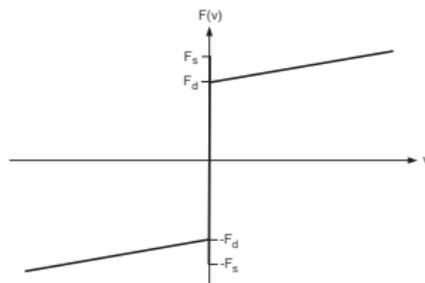
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- ▶ While the velocity of the articulation is zero, the articulation operates in its sticking mode. It will remain in this mode, until the sum of forces applied to this articulation becomes either larger than the positive sticking friction force, F_s , or smaller than the negative sticking friction force, $-F_s$.

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- ▶ When this happens, the articulation comes out of sticking friction, and changes its operational mode to moving either forward or backward. It will remain in that mode, until the velocity of the articulation crosses through zero, at which time the model will return to its sticking mode.

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- ▶ This is a new situation as compared to the electrical switch, because the electrical switch toggles between two different equations one of which is always active. Thus, the number of equations remains the same. In contrast, the friction element adds one equation and one variable to the model, when v becomes 0, and removes them again, when $\text{abs}(F_c)$ becomes larger than the threshold value F_s .

Mechanical Friction III

- ▶ **Modelica** does not allow to add/remove variables and/or equations during the simulation. Therefore, a dummy equation is added that becomes active, when the constraint equation, $v = 0.0$, is removed. The dummy equation is used to provide a unique –but arbitrary– value for F_c during sliding motion. For example, $F_c = 0.0$ is as good a value as any.

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- ▶ The third equation is our meanwhile well-known *switch equation*.

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- ▶ If the velocity, v , is zero in the sticking mode, then also $a = 0$.
- ▶ Hence we can replace the velocity by the acceleration in the switch equation:

$$\begin{aligned}
 F &= \text{if } v > 0 \text{ then } c_f \cdot v + F_d \text{ else} \\
 &\quad \text{if } v < 0 \text{ then } c_f \cdot v - F_d \text{ else } F_c \\
 0 &= \text{if } \textit{Sticking} \text{ then } a \text{ else } F_c
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Mechanical Friction V

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- ▶ This model works, but since we no longer state explicitly that $v = 0.0$, while in sticking mode, there may be a small remaining velocity from the iteration on the state event that subsequently leads to a slow drift.
- ▶ We can avoid that problem by augmenting the model:

```
 $F$  = if  $v > 0$  then  $c_f \cdot v + F_d$  else  
      if  $v < 0$  then  $c_f \cdot v - F_d$  else  $F_c$   
 $0$  = if Sticking then  $a$  else  $F_c$   
when Sticking then  
  reinit( $v, 0$ );  
end when;
```

Mechanical Friction VI

- ▶ We haven't defined yet, how the *discrete state variable*, *Sticking*, is computed by the model. To this end, we need to define, how the switching between the sliding and the sticking phases takes place.

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- ▶ It is advantageous to split the friction force law into the following five different regions:

region:

region conditions:

<i>Forward</i>	:	$v > 0$	and $F = c_f \cdot v + F_d$
<i>StartForward</i>	:	$v = 0$ and $a > 0$	and $F = +F_d$
<i>Sticking</i>	:	$v = 0$ and $a = 0$	and $F \in [-F_s, +F_s]$
<i>StartBackward</i>	:	$v = 0$ and $a < 0$	and $F = -F_d$
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<i>Sticking</i>	: $v = 0$ and $a = 0$	and $F \in [-F_s, +F_s]$
<i>StartBackward</i>	: $v = 0$ and $a < 0$	and $F = -F_d$
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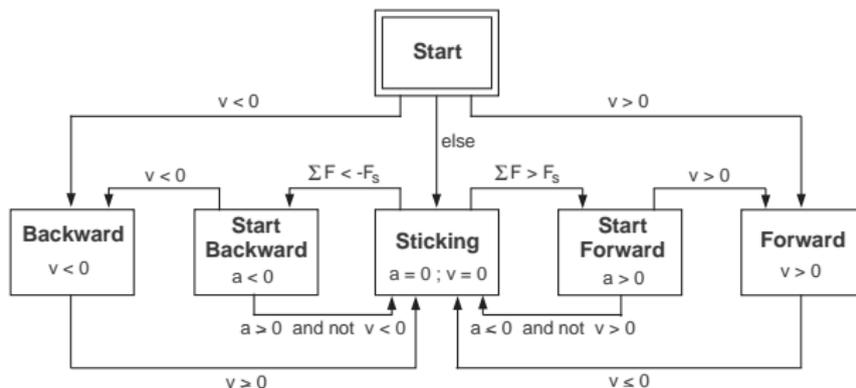
- ▶ Unfortunately, the above five regions cannot be encoded directly, because the equality relation “=” appears in the conditional expressions of **if**-statements. It is not meaningful to test computed real-valued variables for being equal to zero.

Mechanical Friction VII

We shall use an indirect approach. The switching between the five regions is described by a *deterministic finite state machine (DFSM)* represented by the following *state transition diagram*:

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Mechanical Friction VIII

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```

Forward      = pre(Start)           and  $v > 0$  or
                pre(StartForward)    and  $v > 0$  or
                pre(Forward)         and not  $v \leq 0$ ;

Backward    = pre(Start)           and  $v < 0$  or
                pre(StartBackward)   and  $v < 0$  or
                pre(Backward)        and not  $v \geq 0$ ;

StartForward = pre(Sticking)        and  $F_c > +F_s$  or
                pre(StartForward)    and not
                ( $v > 0$  or  $a \leq 0$  and not  $v > 0$ );

StartBackward = pre(Sticking)        and  $F_c < -F_s$  or
                pre(StartBackward)    and not
                ( $v < 0$  or  $a \geq 0$  and not  $v < 0$ );

Sticking     = not (Start or
                Forward or StartForward or
                Backward or StartBackward);

F = if Forward      then  $c_f \cdot v + F_d$  else
      if Backward    then  $c_f \cdot v - F_d$  else
      if StartForward then  $+F_d$            else
      if StartBackward then  $-F_d$          else  $F_c$ ;

0 = if Sticking or Start then  $a$  else  $F_c$ ;

when Sticking and not Start then
  reinit( $v, 0$ );
end when;
```

Mechanical Friction IX

- ▶ This model can be simulated. Unfortunately, the conditional expression accompanying the switch equation is anything but smooth. Consequently, we are forced to use golden section to iterate on the switch equation.

Mechanical Friction IX

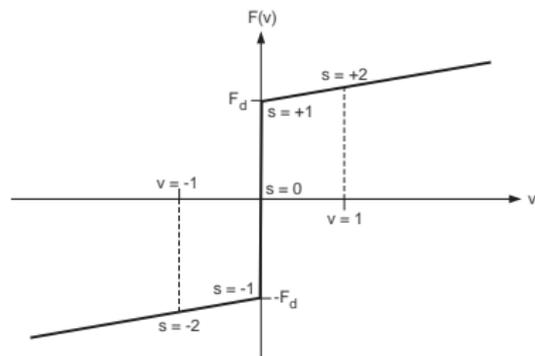
- ▶ This model can be simulated. Unfortunately, the conditional expression accompanying the switch equation is anything but smooth. Consequently, we are forced to use golden section to iterate on the switch equation.
- ▶ Let us see whether we can improve on the situation by using the *parameterized curve description* method.

Mechanical Friction X

A slightly simplified parameterized friction force characteristic is shown below:

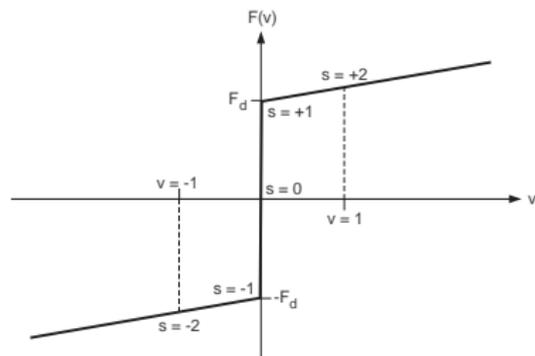
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The curve parameter is defined as follows:

<i>region</i>	<i>s</i>
<i>forward</i>	$v + 1$
<i>sticking</i>	$\frac{F}{F_d}$
<i>backward</i>	$v - 1$

Mechanical Friction XI

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- ▶ Using the new variable, s , we can define the simplified friction model as follows:

```

Forward =  $s > +1$ ;
Backward =  $s < -1$ ;
v = if Forward then  $s - 1$            else
    if Backward then  $s + 1$          else 0;
F = if Forward then  $c_f \cdot (s - 1) + F_d$  else
    if Backward then  $c_f \cdot (s + 1) - F_d$  else  $F_d \cdot s$ ;

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```

- ▶ This model is correct in the sense that it describes unambiguously our intentions of what the model is supposed to accomplish.

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- ▶ When s becomes smaller than $+1$, the model enters its *Sticking* region. In this region, we have the equation; $v = 0$. Thus, the velocity, v , can no longer be treated as a known state variable, and we are confronted with a *conditional index change*.

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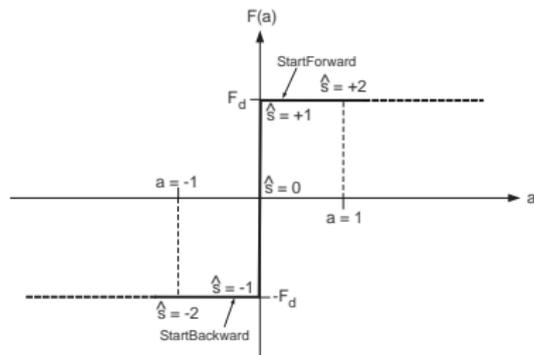
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- ▶ When s becomes smaller than $+1$, the model enters its *Sticking* region. In this region, we have the equation; $v = 0$. Thus, the velocity, v , can no longer be treated as a known state variable, and we are confronted with a *conditional index change*.
- ▶ We can tackle the problem using the same argumentation that had been used already in the previous model: If the velocity, v , is constantly equal to zero over a period of time, then also the acceleration, a , must be constantly equal to zero during that time period.

Mechanical Friction XIII

Hence we parameterize the friction force characteristic differently:

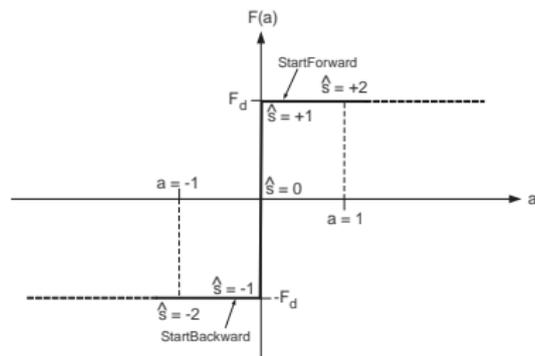
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The curve parameter is defined as follows:

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<i>forward</i>	$a + 1$
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<i>backward</i>	$a - 1$

Mechanical Friction XIV

We code the so parameterized force characteristic as follows:

```
StartForward =  $\hat{s} > +1$ ;  
StartBackward =  $\hat{s} < -1$ ;  
a = if StartForward then  $\hat{s} - 1$  else  
    if StartBackward then  $\hat{s} + 1$  else 0;  
F = if StartForward then  $+F_d$  else  
    if StartBackward then  $-F_d$  else  $F_d \cdot \hat{s}$ ;
```

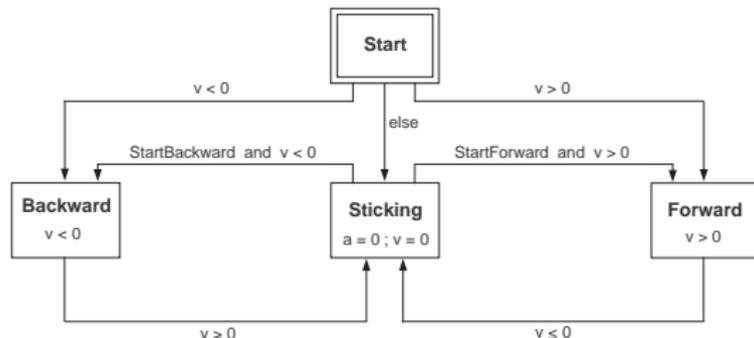
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    if StartBackward then  $\hat{s} + 1$  else 0;
F = if StartForward then  $+F_d$  else
    if StartBackward then  $-F_d$  else  $F_d \cdot \hat{s}$ ;
  
```

The following *state transition diagram* describes the transitions between the different modes:



Mechanical Friction XV

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- ▶ The *StartForward* and *StartBackward* modes of operation are no longer considered separate regions. Instead, they are contained within the *Sticking* region model. They only represent different aspects of the *Sticking* region.
- ▶ This is the friction model that is currently being offered as part of the *mechanics sub-library* of the **Modelica Standard Library**.

Petri Nets

We shall now demonstrate that it is always possible to decompose complex (combined) event conditions into sets of simple event conditions that consist of a single relational operator only.

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Thus, all zero-crossing functions can be made smooth.

To this end, we shall introduce a new model description tool: the *Petri net*.

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- ▶ A transition may fire, when an external firing condition is true, if the conditions concerning the necessary numbers of tokens held by its input places are also true.
- ▶ If one place feeds several transitions, additional logic may be required to determine firing preferences in the case of simultaneous events, i.e., in the case where the external firing conditions of several transitions become true simultaneously, because there may be enough tokens in the input place to fire one or the other of these transitions, but not all of them.

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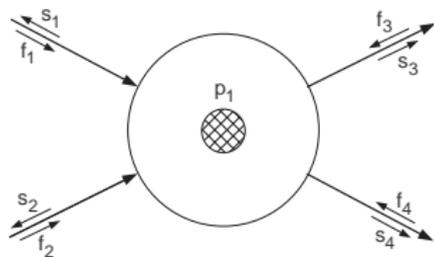
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- ▶ *Priority Petri nets* resolve the ambiguity associated with multiple transitions being able to fire simultaneously by associating a prioritization scheme to these transitions.
- ▶ *Normal priority Petri nets (NPPNs)* are normal Petri nets employing prioritization schemes in all of their transitions.

Petri Nets IV

A NPPN place with two inputs and two outputs is shown below:

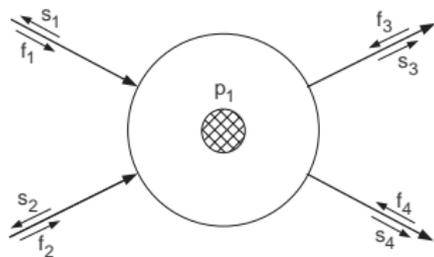
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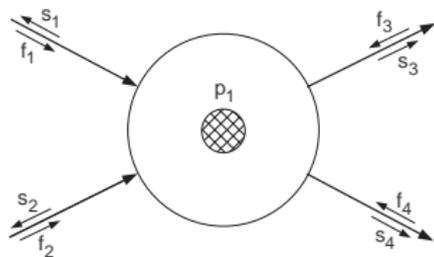
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The place passes state information, s_i , to all neighboring transitions, and in turn receives firing information, f_i , back from these transitions.

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The place passes state information, s_i , to all neighboring transitions, and in turn receives firing information, f_j , back from these transitions.

The NPPN place could be governed by the following equations:

$$s_1 = \text{pre}(p_1)$$

$$s_2 = \text{pre}(p_1) \text{ or } f_1$$

$$s_3 = \text{pre}(p_1)$$

$$s_4 = \text{pre}(p_1) \text{ and not } f_3$$

$$p_1 = [\text{pre}(p_1) \text{ and not } (f_3 \text{ or } f_4)] \text{ or } f_1 \text{ or } f_2$$

Petri Nets V

- ▶ The place first provides the first input transition, t_1 , with its state information. Transition t_1 needs to know this information, because, due to the single-token capacity limitation, it cannot fire, unless the place, p_1 , is currently unoccupied. The place receives the firing information, f_1 , back from transition t_1 . If t_1 fires, it means that it is going to place a new token at p_1 .

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- ▶ The place then provides the appropriate state information, s_2 , to the second input transition, t_2 . Transition t_2 is assigned a lower priority than transition t_1 . Transition t_2 is not allowed to fire if either there is already a token at place p_1 , or if the other input transition, t_1 , decided to fire, because if both transitions were to fire simultaneously, they both would try to place a token at p_1 , which would violate the imposed capacity limit of one.

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- ▶ The place then provides its state information to the first output transition, t_3 . Transition t_3 is allowed to fire if a token is currently at p_1 . If it fires, it will take the token away from place p_1 .

Petri Nets VI

- ▶ The place then provides its state information to the second output transition, t_4 . Transition t_4 is assigned a lower priority than transition t_3 . Transition t_4 is not allowed to fire, unless there is currently a token at place p_1 and transition t_3 has not decided to fire, because if both transitions were to fire simultaneously, they both would fight over who gets to remove the token from p_1 .

Petri Nets VI

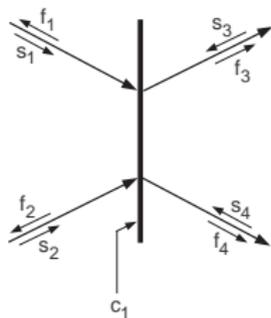
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- ▶ Finally, the place must update its own state information. If there was a token at p_1 before, and neither of the two output transitions, t_3 or t_4 , has taken it away, or, if one of the two input transitions, t_1 or t_2 , has placed a new token at p_1 , there will be a token at that place during the next cycle.

Petri Nets VII

Let us now look at a transition with two input places and two output places:

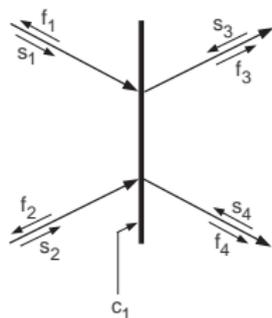
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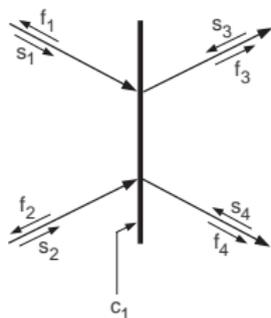
Let us now look at a transition with two input places and two output places:



The transition is allowed to fire along all of its connections, when the external firing condition, c_1 , is true, and if each of the input places holds a token (or more precisely, if the state information arriving from all of the input places is *true*), and if none of the output places holds a token (or more precisely, if the state information of none of the output places is *true*).

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This logic can be described by the following set of equations:

$$\text{fire} = c_1 \text{ and } s_1 \text{ and } s_2 \text{ and not } (s_3 \text{ or } s_4)$$

$$f_1 = \text{fire}$$

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Petri Nets VIII

Deterministic finite state machines (DFSMs) can be modeled as *normal priority Petri nets* with the additional constraints that there is only one token in the system that is initially located at the *Start* place. Furthermore, DFSMs map to NPPNs, in which each transition is associated with exactly one input place and one output place.

Petri Nets VIII

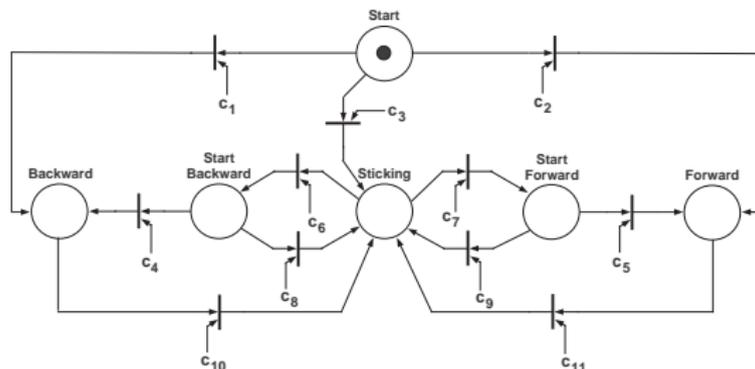
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- ▶ In the past, we had many different discrete event blocks representing the actions to be taken, when one or the other of the zero-crossing functions triggered an event. This is no longer the case.
- ▶ All of the discrete equations governing both *places* and *transitions* are valid at every event, since they were formulated as functions of the current location of the tokens, i.e., they were functions of the discrete state that the system is currently operating in.

Petri Nets X

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- ▶ There is the set of *zero-crossing functions* that are all evaluated in parallel, while the continuous subsystem is being simulated. If a state event is being triggered by one of them, an iteration (or interpolation) takes place to locate the event time as accurately as necessary.
- ▶ At that moment, the third set of simultaneous equations is being executed. These are the *(possibly implicitly defined) algebraic and difference equations* describing the discrete subsystem. The discrete equations are executed iteratively, until no discrete state changes occur any longer. When this happens, we have found our new initial state, from which we can start the continuous simulation afresh.

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- ▶ It is the job of the *model compiler* to dissect the model description that the user supplies, and translate it down to sets of simultaneous equations that can be simulated without numerical difficulties.
- ▶ As this class concerns itself with the set of algorithms underlying a powerful modeling and simulation environment, such as **Dymola**, we had to show step by step, how model equations need to be preconditioned, until they are finally in a form such that they can be simulated without difficulties. Yet, it is inconvenient to translate every model that we came across manually down to such a form.

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- ▶ For example, the discrete “equation” $p_1 = \text{not pre}(p_1)$; should not be contained in the set of discrete equations, as this will lead to an oscillation between the two states *true* and *false* that will never end.
- ▶ If we mean to toggle between two discrete states as a response to a state-event being triggered (a fairly common situation), we need to model this using two separate places with transitions back and forth that get fired by zero-crossing functions.

Petri Nets XIII

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- ▶ *or*-conditions can be mapped to a set of parallel transitions located between the same two places. They can thus be easily implemented.
- ▶ *and*-conditions are harder to implement, as they would require transitions to be placed in series with each other. Unfortunately, this cannot be done without introducing a new place between them. Thus, *and*-conditions invariably call for an increase in the number of discrete states.

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- ▶ We don't need to draw the modified Petri net, as it looks exactly like the previous one. Only the interpretation of the zero-crossing functions is now different:

$$c_1 = v < 0$$

$$c_2 = v > 0$$

$$c_3 = v == 0$$

$$c_4 = v < 0$$

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$$c_6 = \hat{s} < -1$$

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- ▶ As expected, all of the zero-crossing functions are now simple functions consisting of a single relational operation only.

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- ▶ We then showed that *inlining integrators* that constrain the causality of switches often helps to avoid divisions by zero. To this end, we introduced the concept of *mixed-mode integration*.
- ▶ Next, we looked at *mechanical friction characteristics* as a very important example of a complex variable structure system that exhibits all of the theoretical difficulties illuminated before. We made use of *state transition diagrams* and, more abstractly, *deterministic finite state machines (DFSMs)* to describe the different regions of operation of a friction characteristic and the conditions for switching from one region to another.

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- ▶ Hence all discontinuous systems can be described by models that can be simulated using a *synchronous data flow* approach.
- ▶ We showed that the Petri-net representation makes it furthermore possible to reduce all zero-crossing functions to simple Boolean expressions containing a single relational operator that can be implemented using smooth functions.

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