Modia – A Prototyping Platform for Next Generation Modeling And Simulation Based on Julia

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Outline

- Motivation - The *Modia* project
- Introduction to *Modia* language
- *Modiator* web app
- *ModiaMedia*
- Symbolic algorithms
- Summary

Modelica Challenges

- Modelica is powerful (equations, objects, connections)
  - Although static, requiring recompilation if:
    - An array dimension is changing
    - A component class is changing
    - A medium is changing
- Modelica algorithms and functions lack functionalities:
  - Modern data structures
  - Parallelization
  - …
- It is possible to build complex system models, but:
  - Sometimes hard to understand models (3D, media/fluid models, …)
  - Translation should be faster
  - Simulation should be faster

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Innovation platform - *Modia*

Based on modern language – Julia

- Dynamic typing, Matlab-like notation
- Static typing, efficient, data structures (as C++)
- Multiple dispatch
- Metaprogramming
  - for domain specific language extensions
  - for symbolic processing
- Just-in-time compilation

Open source project consisting of several Julia packages (github.com/ModiaSim)

Modia	Equation-based modeling
Modiator	2D/3D model editor
ModiaMath	Simulation environment
Modia3D	3D geometry and 3D mechanics
ModiaMedia	Thermodynamic property models
Modelia	Modelica model importer (partial)

Contributors:
Hilding Elmqvist, Toivo Henningsson, Martin Otter, Andrea Neumayr, Oskar Åström, Chris Laughman

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Connectors and Components - Electrical

Modelica

```
@model Pin begin
  v=Float()
  i=Float(flow=true)
end

@model OnePort begin
  p=Pin()
  n=Pin()
  v=Float()
  i=Float()
@equations begin
  v = p.v - n.v # Voltage drop
  0 = p.i + n.i # KCL within component
  i = p.i
  end
end

@model Resistor begin # Ideal linear electrical resistor
  @extends OnePort()
  @inherits i, v
  R=1 # Resistance
@equations begin
  R*i = v
  end
end
```

```
connector Pin
  Modelica.SIunits.Voltage v;
  flow Modelica.SIunits.Current I;
end Pin;

partial model OnePort
  SI.Voltage v;
  SI.Current i;
  PositivePin p;
  NegativePin n;
equation
  v = p.v - n.v;
  0 = p.i + n.i;
  i = p.i;
end OnePort;

model Resistor
  parameter Modelica.SIunits.Resistance R;
  extends Modelica.Electrical.Analog.Interfaces.OnePort;
equation
  v = R*i;
end Resistor;
```

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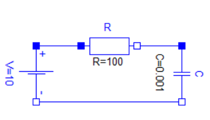
Elmqvist/Henningsson/Otter 2017: Innovations for Future Modelica

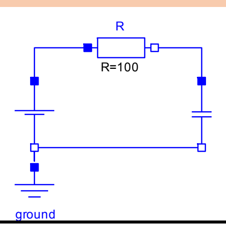
Coupled Models - Electrical Circuit

Modelica

```
@model LPfilter begin
  R = Resistor(R=100)
  C = Capacitor(C=0.001)
  V = ConstantVoltage(V=10)
@equations begin
  connect(R.n, C.p)
  connect(R.p, V.p)
  connect(V.n, C.n)
  end
end
```

```
model LPfilter
  Resistor R(R=100);
  Capacitor C(C=0.001);
  ConstantVoltage V(V=10);
  Ground ground;
equation
  connect(R.n, C.p);
  connect(R.p, V.p);
  connect(V.n, C.n);
  connect(V.n, ground.p);
end Lpfilter;
```





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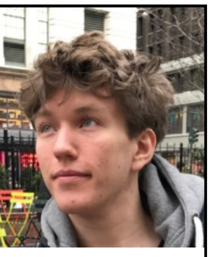
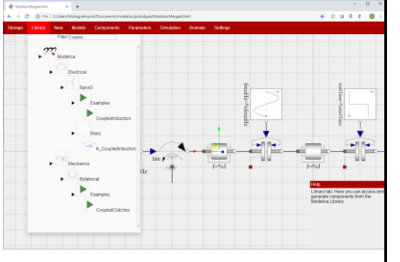
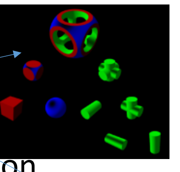
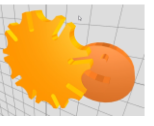
Modiator – web app

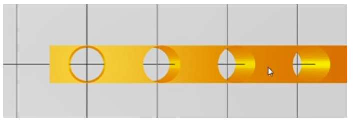
- Summer 2019 prototype
- Summer intern: Oskar Åström
- Joint project between Modelon and Mogram
- Cooperation with Martin Otter, DLR
- Modelica diagrams
- Exploring fundamentals
  - CSG – Constructive Solid Modeling
  - Shape parametrization
- Focus: 3D model composition and animation
  - Modia3D
  - Modelica…MultiBody











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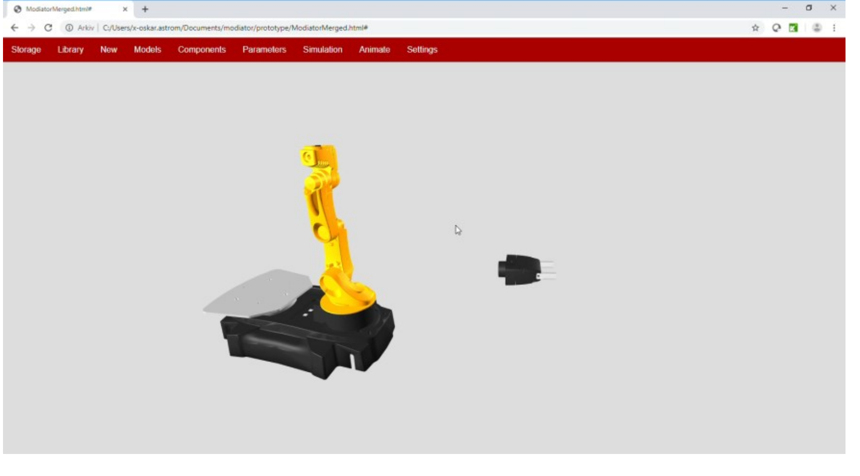
3D model composition

- Mechanism composition
- Introducing joints
- Parametrization
- Immediate kinematic animation
- Exploded view



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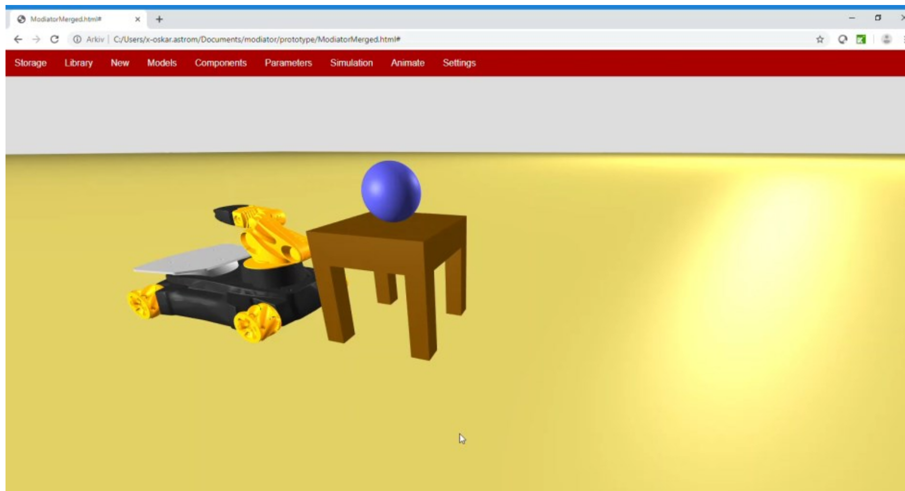
3D Animation

- Generate *Modia3D* model
  - Determine properties from geometries (mass, ...)
  - 3D mechanics algorithms
  - Collision handling
  - Fast translation
- Client/server communication between web app and Julia
- Simulate
- Animate result in *Modiator*



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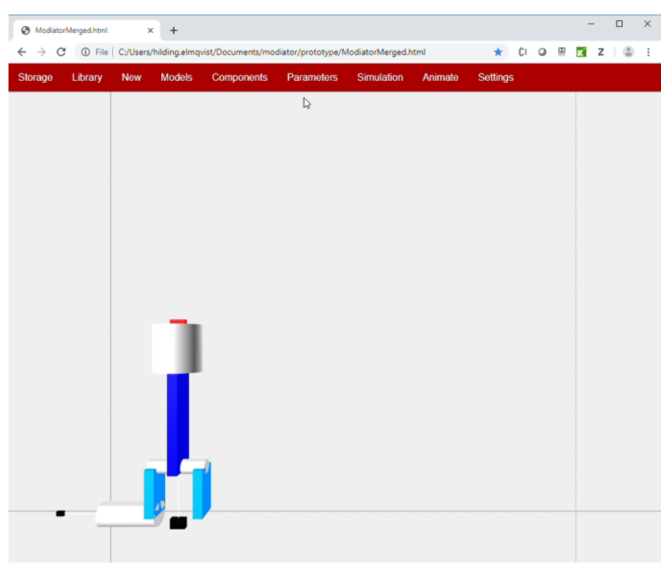
Modelica Multibody 3D parametric preview

- Kinematic animation
- Parametric animation
- Spanning tree view
- Interpretation of Modelica AST
- Evaluation of Modelica expressions



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ModiaMedia - Thermodynamic property models

Developers: Martin Otter (DLR), Hilding Elmqvist (Mogram), Chris Laughman (MERL); Paper at Modelica'2019

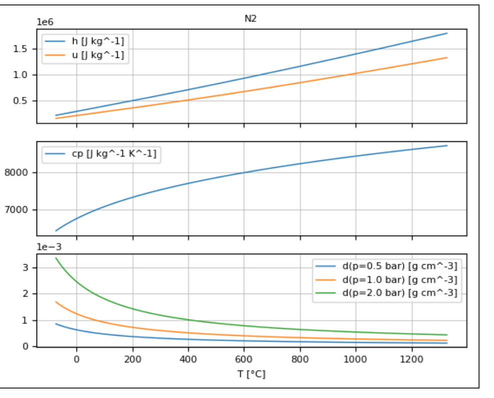
```
using ModiaMedia

Medium = getMedium("N2")       # dictionary

p = 1e5
T = 300.0
state = setState_pT(Medium, p, T)  # construct
setState_pT!(state, 2*p, 2*T)       # update

d = density(state)               # get other properties
h = specificEnthalpy(state)

listMedia()                  # list all supported media
standardPlot(Medium)    # plot Medium
```



- **Much simpler and more powerful as Modelica.Media**
- Fluid network: **state** propagated/updated along connection structure (Medium defined at **one** state instance)

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Symbolic Algorithms

- For $\mathbf{0} = \mathbf{f}(\dot{\mathbf{x}}, \mathbf{x}, t)$
- Can be used directly in current Modelica tools

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Modelica translation today - flattening

- Object-oriented modeling approach
  - allows building large models with millions of equations
- Semantic specification is based on **flattening**
  - **i.e. cloning variables and equations** of each component instance
- And most tools also expands matrix equations

Negative consequences:

- A lot of **memory** is needed for variables and equations during translation
- **Translation time** is unnecessary long
  - same analysis (flattening, symbolic processing, etc) is performed repeatedly for each instance of a component
- **C-code** gets large and **compilation** takes long time

Remedy: Separate Translation

- Parts of the equations of a component
  - are always executed in the **same order** and with the **same causality**
  - independently of how the component is connected
- Such sequences of equations can be put into **functions**
  - which are reused for all components of the same class
  - less C-code gives **shorter compilation time**
- Finding such sequences can be made once for each model class
  - **faster translation** and **less memory use**

Component Model Equations

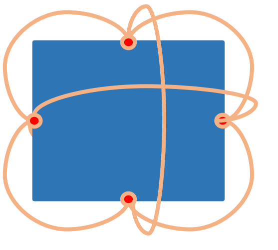
DAE:

$f(\dot{x}, x, c_p, c_f, u, y, v, p)$=0

- x – differentiated variables
- c_p – potentials of the connectors
- c_f – flows and streams of the connectors
- u – inputs
- y – outputs
- v – other variables
- p – parameters
- dim(f) = dim($\dot{x}$)+dim(c_p)+dim(y)+dim(v)

Generic environment of model:

- Generic environment needs to relate all connector variables
- $g(c_p, c_f, u, y)$=0
  - dim(g) = dim(c_f)+dim(u)
  - g has full incidence
- Might also contain derivatives



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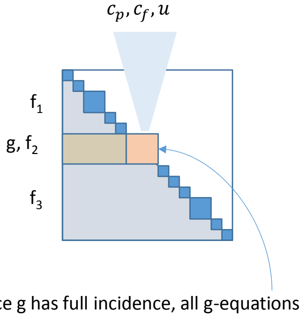
Model equations partitioning

- First blocks (always same causality, use function):
  - $\dot{x}_1, y_1, v_1 = f_1(\boldsymbol{x}, \boldsymbol{p})$
- Middle block (f_2 kept as equations):
  - $g(c_p, c_f, u, y)$=0
  - $f_2(\dot{\boldsymbol{x}}_1, \dot{x}_2, \boldsymbol{x}, c_p, c_f, u, \boldsymbol{y}_1, y_2, \boldsymbol{v}_1, v_2, \boldsymbol{p})$=0
- Last blocks (always same causality, use function):
  - $\dot{x}_3, y_3, v_3$=$f_3(\dot{\boldsymbol{x}}_1, \dot{\boldsymbol{x}}_2, \boldsymbol{x}, \boldsymbol{c}_p, \boldsymbol{c}_f, \boldsymbol{u}, \boldsymbol{y}_1, \boldsymbol{y}_2, \boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{p})$

Perform BLT on f and g function incidences



Since g has full incidence, all g-equations will appear in the same block

Known variables marked in **bold face**

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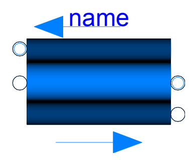
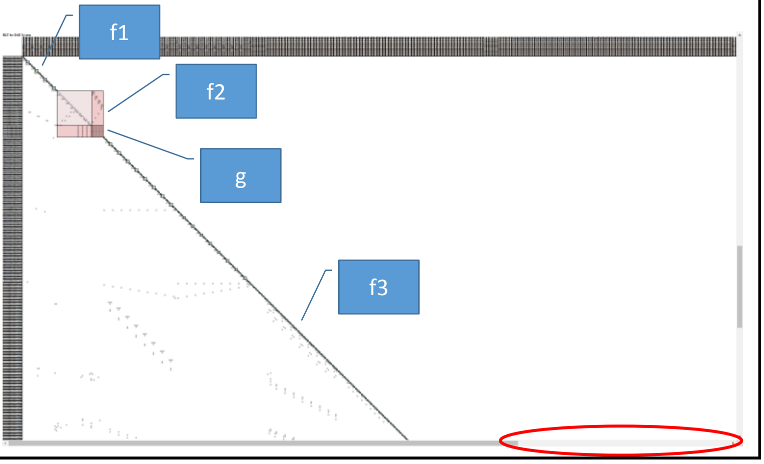
Example: Heat exchanger model

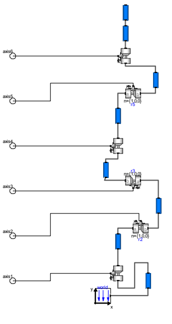


MSL BasicHX

- flow models close to connectors
- **10 spatial segments**
- 50 dynamic states
- 514 equations
- dim(f2) = 24



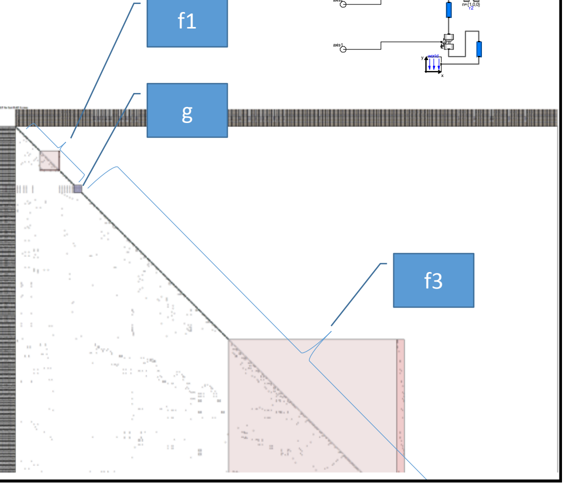
Example: Multibody Robot model



MSL Robot with der(phi)

- With der(phi) in g(…)
  to enable connecting dampers
- 12 dynamic states
- 391 equations
- dim(f2) = 0

- Modia3D is a manual
  implementation of this approach



Separate Translation - Summary

- Systematic method for splitting model equations into acausal and causal partitions
  - User does not need to consider which equations can be moved to functions
  - Local index reduction is performed
  - Global index reduction requires automatic differentiation of the functions
- Limited testing shows that substantial part of the equations can be moved to separately compiled functions
- Less time and memory for both translation and simulation
- This approach could be combined into a generalized FMU.

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Index Reduction of Array Equations

Core algorithm in Modelica tools

- Structural algorithm to reduce DAE index to 0 (= solve state constraints)
- Often: *Pantelides 1988*.
- Map scalar equations ⟶ scalar equations (array properties lost during transformation)

New algorithm *Otter, Elmqvist 2017 (section 3)*

- Generalization of *Pantelides 1988*
- Map array equations ⟶ array equations
- More efficient machine code possible

Example

$$
\begin{aligned}
\mathbf{r} &= \mathbf{n}s \\
\mathbf{v} &= \dot{\mathbf{r}} \\
m\dot{\mathbf{v}} &= \mathbf{f} + m\mathbf{g} + \mathbf{u} \\
0 &= \mathbf{n}\cdot\mathbf{f} \\
\mathbf{u} &= -(cs + d\dot{s})\mathbf{n}
\end{aligned}
$$

BLT Block 1	*solve for*
$\mathbf{u} = -(cs + d\dot{s})\mathbf{n}$	$\mathbf{u}$
BLT Block 2	
BLT Block 2.1	
$\mathbf{r} = \mathbf{n}s$	$s, \mathbf{r}$
BLT Block 2.2	
$\dot{\mathbf{r}} = \mathbf{n}\dot{s}$ $\mathbf{v} = \dot{\mathbf{r}}$	$\dot{s}, \dot{\mathbf{r}}, \mathbf{v}$
BLT Block 2.3	
$\ddot{\mathbf{r}} = \mathbf{n}\ddot{s}$ $\dot{\mathbf{v}} = \ddot{\mathbf{r}}$ $m\dot{\mathbf{v}} = \mathbf{f} + m\mathbf{g} + \mathbf{u}$ $\mathbf{0} = \mathbf{n}\cdot\mathbf{f}$	$\ddot{s}, \ddot{\mathbf{r}}, \dot{\mathbf{v}}, \mathbf{f}$

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Tearing with retained solution space

Core algorithm in Modelica tools

- Reduce the size of algebraic equation systems
- Reduce number of states

$$\mathbf{0} = \boldsymbol{g}(\boldsymbol{z}) \longrightarrow \begin{array}{l} \boldsymbol{z}_e := \boldsymbol{g}_e(\boldsymbol{z}_e, \boldsymbol{z}_t) \\ 0 = \boldsymbol{g}_r(\boldsymbol{z}_e, \boldsymbol{z}_t) \end{array}$$

$\boldsymbol{z} = [\boldsymbol{z}_e, \boldsymbol{z}_t]$
solve explicitly as much as possible, without changing solution space

Example

$$\begin{array}{l} z_1 = f_1(z_4) \\ z_2 = f_2(z_1, z_5) \\ z_3 = f_3(z_2, z_1) \\ z_4 = f_4(z_3, z_2) \end{array} \rightarrow \begin{array}{l} \text{input: } z_4 \\ \text{output: } r \\ z_1 := f_1(z_4) \\ z_2 := f_2(z_1, z_5) \\ z_3 := f_3(z_2, z_1) \\ r = z_4 - f_4(z_3, z_2) \end{array}$$

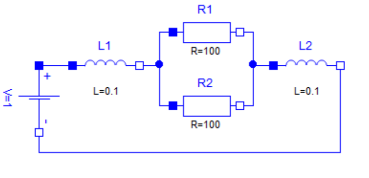
New algorithm:

Otter, Elmqvist 1999 (unpublished) +
Bender, Fineman, Gilbert, Tarjan 2016 (incremental cycle detection in DAGs)
→ *Otter, Elmqvist 2017 (section 4.6)*

O(n) ≤ tearing ≤ O(nm)
Example: Loop with 1 million equations → 1 equation (needs 2s)

Exact Removal of Singularities

Example



Modelica tools can fail on well-defined models:

- Structurally singular at compile-time
- Singular Jacobian at run-time

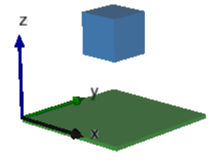
New algorithm *Otter, Elmqvist 2017 (section 5)*

- Extract all linear equations with Integer coefficients from DAE system (e.g.: $0 = i_1 + i_2$; $u_{rel} = u_2 - u_1$):
  $\rightarrow \mathbf{A} \cdot \boldsymbol{x} = \mathbf{B}$, $\mathbf{A} \in \mathbb{Z}^{na1 \times na2}$, $\mathbf{B} \in \mathbb{Z}^{na1 \times nb2}$
- Remove all singularities exactly!!!
- Use as pre-processing step

- Remove redundant equation:
  -L2.n.i - V.n.i = 0
- Make potentials well-defined by adding equation:
  L2.n.v = 0
- Make state constraints structurally visible by replacing
  -R1.p.i - R2.p.i - L1.n.i = 0
  with
  -L1.p.i + L2.p.i = 0

No dynamic state selection

Example



Modelica tools transform $\mathbf{0} = \mathbf{f}_1\,(\dot{\mathbf{x}}, \mathbf{x}, t)$
(conceptually) to index 0 form: $\dot{\boldsymbol{x}}_{red} = \mathbf{f}_2(\mathbf{x}_{red}, t)$

- Sparseness of $\mathbf{f}_1$ might get lost
- Might require dynamic state selection ($\mathbf{x}_{red}$ changed during simulation; might not work well)

New proposal *Otter, Elmqvist 2017*

Transform to special index 1 form

$$\begin{bmatrix} \mathbf{f}_d(\dot{\boldsymbol{x}}_{red}, \mathbf{x}_{red}, t) \\ \mathbf{f}_c(\mathbf{x}_{red}, t) \end{bmatrix} = \mathbf{0} \qquad \begin{bmatrix} \dfrac{\partial \mathbf{f}_d}{\partial \dot{\mathbf{x}}_{red}} \\ \dfrac{\partial \mathbf{f}_c}{\partial \mathbf{x}_{red}} \end{bmatrix} \text{ is regular}$$

- Sparseness is not changed
- No dynamic state selection

Free Body Rotation (with quaternions)

$$\boldsymbol{\omega} = 2\begin{bmatrix} q_4 & q_3 & -q_2 & -q_1 \\ -q_3 & q_4 & q_1 & -q_2 \\ q_2 & -q_1 & q_4 & -q_3 \end{bmatrix} \cdot \dot{\boldsymbol{q}}$$
$$\boldsymbol{\tau}(t) = \boldsymbol{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{I}$$
$$1 = \boldsymbol{q}^T\boldsymbol{q}$$

- Directly integrate equations (already in special index 1 form)
- Initialization/events:
  - new $\mathbf{x}_{red}$: use Dirac impulse
  - new $\dot{\boldsymbol{x}}_{red}$: use $\frac{d}{dt}(1 = \boldsymbol{q}^T\boldsymbol{q})$

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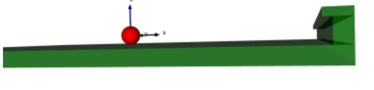
No dynamic state selection - examples

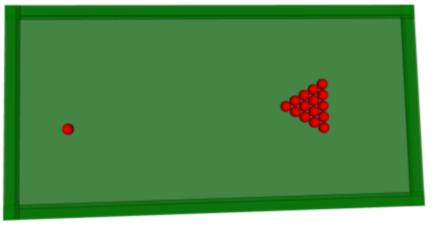
Body attached with spherical joint to ground
(= 7 equations)

$$\boldsymbol{\omega} = 2\begin{bmatrix} q_4 & q_3 & -q_2 & -q_1 \\ -q_3 & q_4 & q_1 & -q_2 \\ q_2 & -q_1 & q_4 & -q_3 \end{bmatrix} \cdot \dot{\boldsymbol{q}}$$
$$\boldsymbol{\tau}(t) = \boldsymbol{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{I}$$
$$1 = \boldsymbol{q}^T\boldsymbol{q}$$

Modia about 40 % faster as a Modelica tool:

- Modelica: index 0 DAE, changing states, DASSL, 4000 model calls
- Modia : index 1 DAE, fixed states , IDA , 2700 model calls





16 free flying bodies à 13 states = 208 states
≈ 200 possible collision pairs

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Multi-mode systems with impulses

Example

Previous multi-mode attempts of limited use:

- Changing structure can lead to index change + Dirac impulse
- Not supported by Modelica tools

New proposal

Benveniste, Caillaud, Elmqvist, Ghorbal, Otter, Pouzet 2019

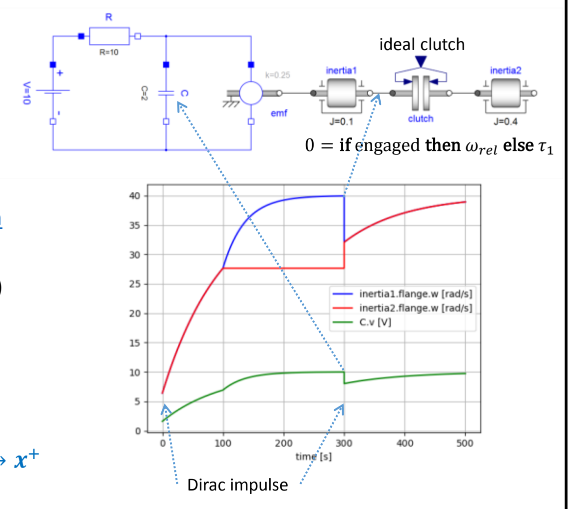
[Multi-Mode DAE Models: Challenges, Theory and Implementation]

Requirement: Special index 1 form linear in derivatives (+ other req.)

$$0 = \begin{bmatrix} \boldsymbol{A}(\boldsymbol{x},t)\dot{\boldsymbol{x}} + \boldsymbol{b}(\boldsymbol{x},t) \\ \boldsymbol{f}_c(\boldsymbol{x},t) \end{bmatrix} \quad (= \boldsymbol{f}_d(\dot{\boldsymbol{x}},\boldsymbol{x},t))$$

Compute $\boldsymbol{x}^+$ from $\boldsymbol{x}^-$ at t_{event}:

implicit Euler $h \rightarrow 0$ (hard) or $0 = \begin{bmatrix} \boldsymbol{A}(\boldsymbol{x}^+, t_{event})(\boldsymbol{x}^+ - \boldsymbol{x}^-) \\ \boldsymbol{f}_c(\boldsymbol{x}^+, t_{event}) \end{bmatrix} \rightarrow \boldsymbol{x}^+$



If index 0 ↔ 1: without re-compilation

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Summary

- Modelica needs better **scalability**
  - since users need to simulate more and more complex product designs
- The Modia project provides **freedom for innovation**
- Several **new algorithms** have been designed and tested
  - could be integrated in Modelica tools
- **New user experiences** are evaluated

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