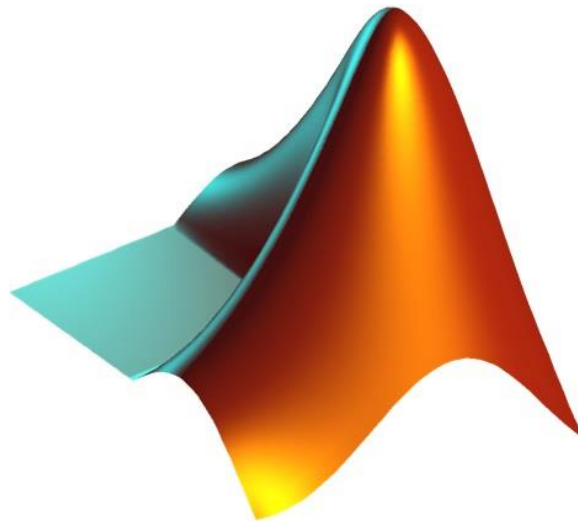


# MATLAB / Simulink Lab Course

## Physical Modeling



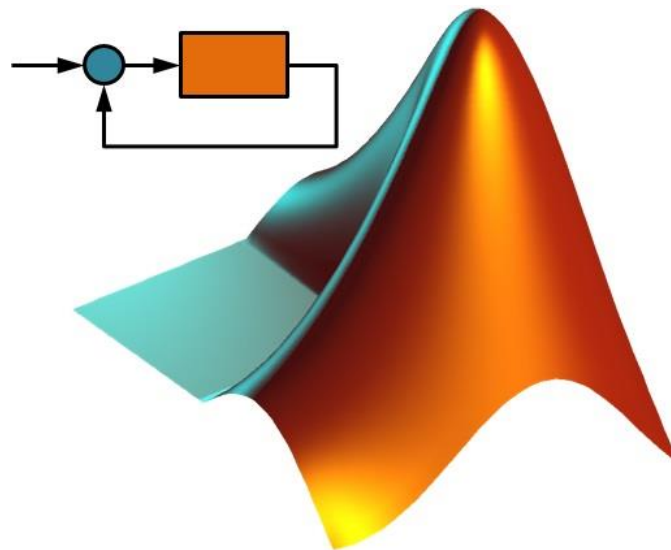
# Outline

1. Motivation
  - Reasons for Physical Modeling
2. Introduction
  - What is Physical Modeling?
  - Simscape Toolbox
3. Multibody Simulation with Simscape Multibody Modeling
  - Basics of Multibody Simulation
  - Defining Bodies, Joints and Coordinate Frames
  - Assembling Mechanisms
  - Visualization
4. Configure Joint Settings
  - Sensing and Logging Joint Quantities
  - Actuating Joints (Force / Torque or Motion)
5. Combining Simscape Multibody and Simulink Models
6. CAD Import

# Introduction – Reasons for Physical Modeling

- **Reasons** for Physical Modeling
  - **Easy and intuitive modeling** of even complex and multi-domain physical systems
  - **Timesaving** and **cost-saving** modeling → faster modeling and insight into the system
  - **Virtual prototypes** in early stage of development
  - Observing variables without changing the model

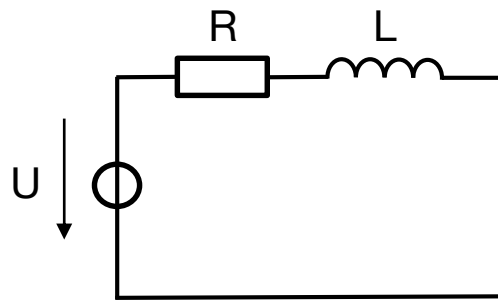
# 1. Introduction



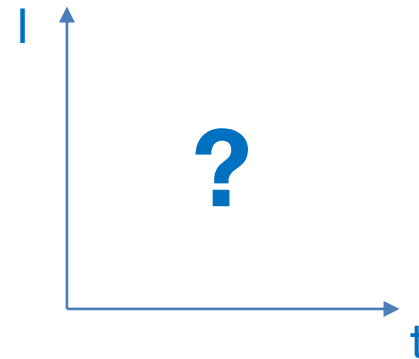
## Introduction – What is Physical Modeling?

- Example 1: How to **model** this electric circuit using **ordinary methods**?

**Goal:** Calculate current over time



$$U = 12 \text{ V}; R = 6 \, \Omega; L = 1 \text{ H}$$



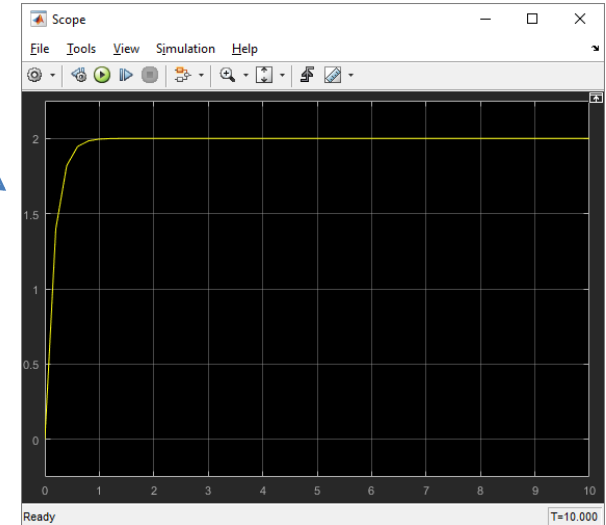
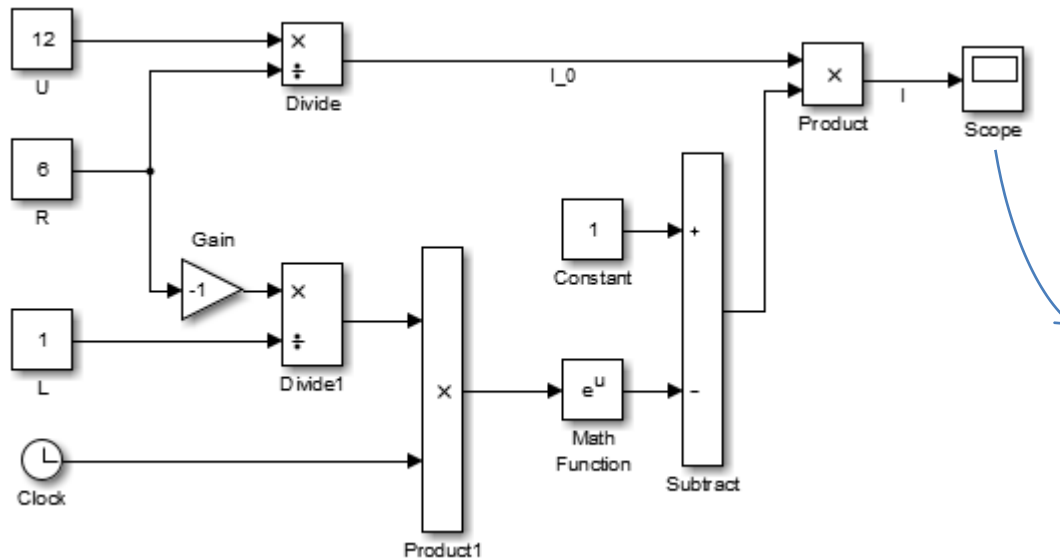
- Equations** describing the system behaviour

$$I = \frac{U}{R}$$

$$I_L(t) = I \cdot \left(1 - e^{-\frac{R}{L}t}\right)$$

# Introduction – What is Physical Modeling?

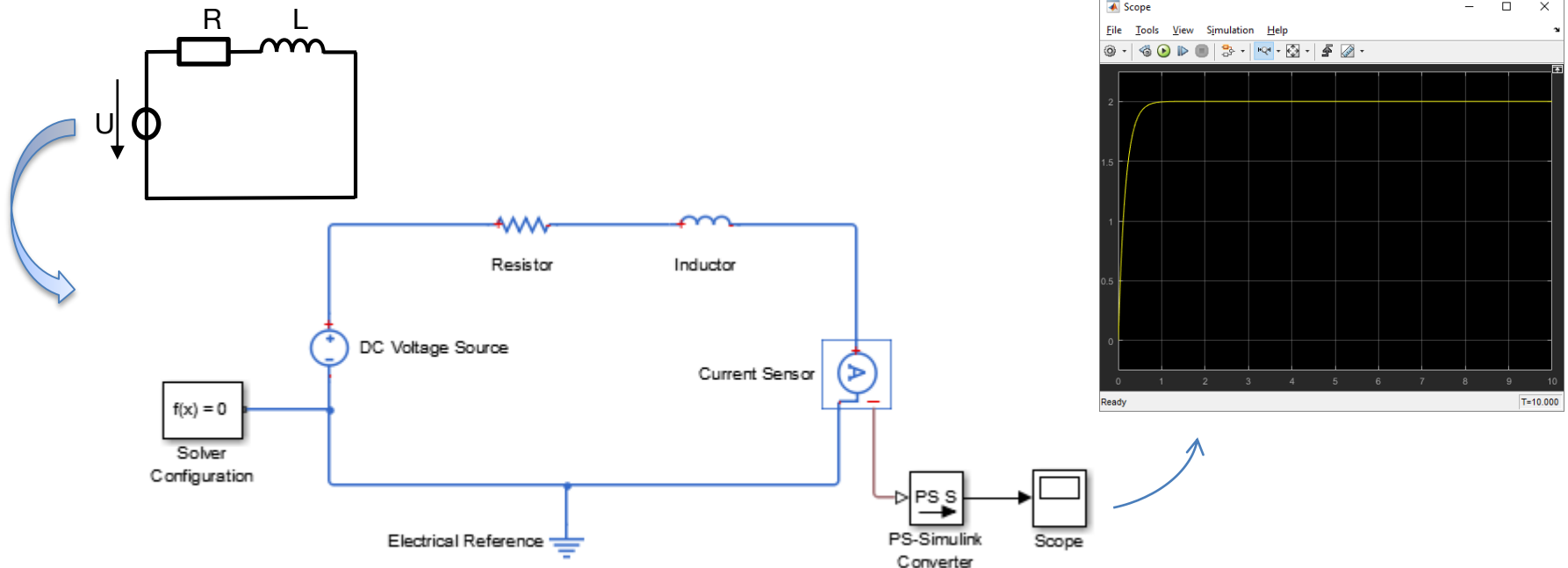
- Implementing a Simulink diagram



Note: A Simulink diagram represents a **chain of mathematical operations**. The graph is a **directed graph** and the "lines" are representing **numerical signals**.

# Introduction – What is Physical Modeling?

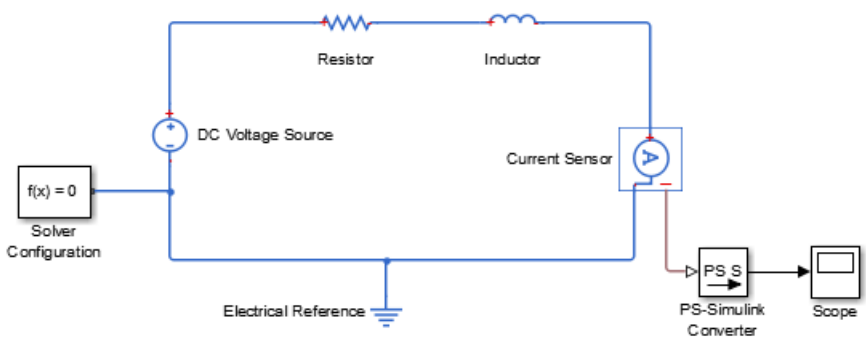
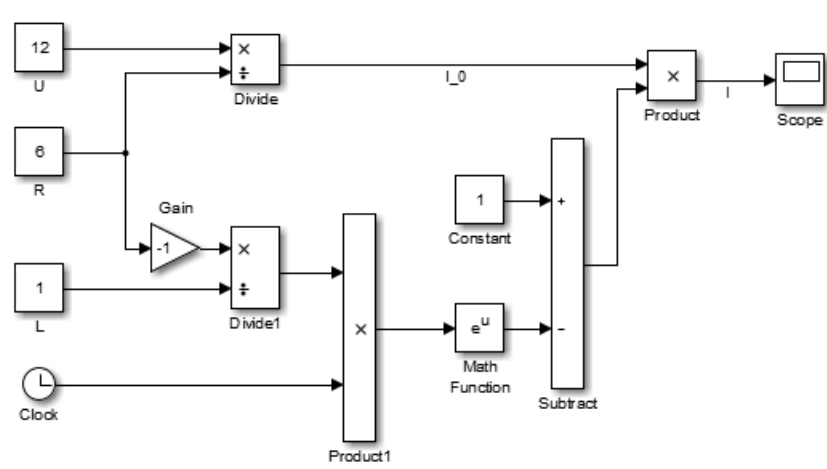
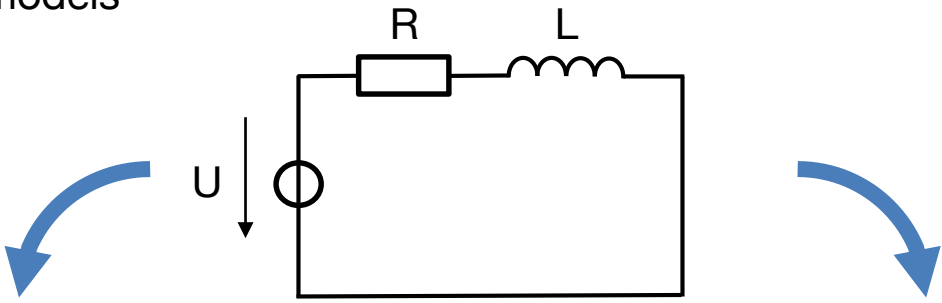
- How to **model** the same system using **Physical Modeling (Simscape)**:



A Simscape graph represents **differential algebraic equations (DAEs)**. These graphs are **undirected graphs** and "lines" are **physical signals (PS)** that **link equations**.

# Introduction – What is Physical Modeling?

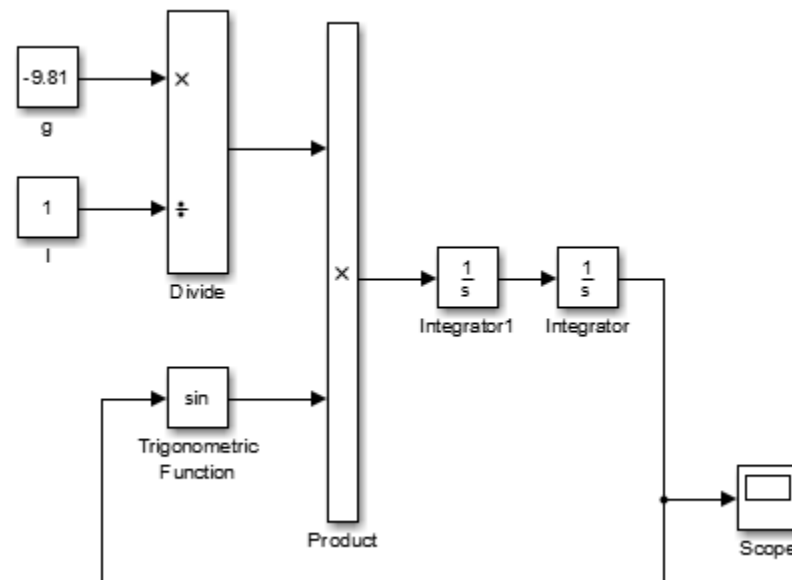
- Comparing both models





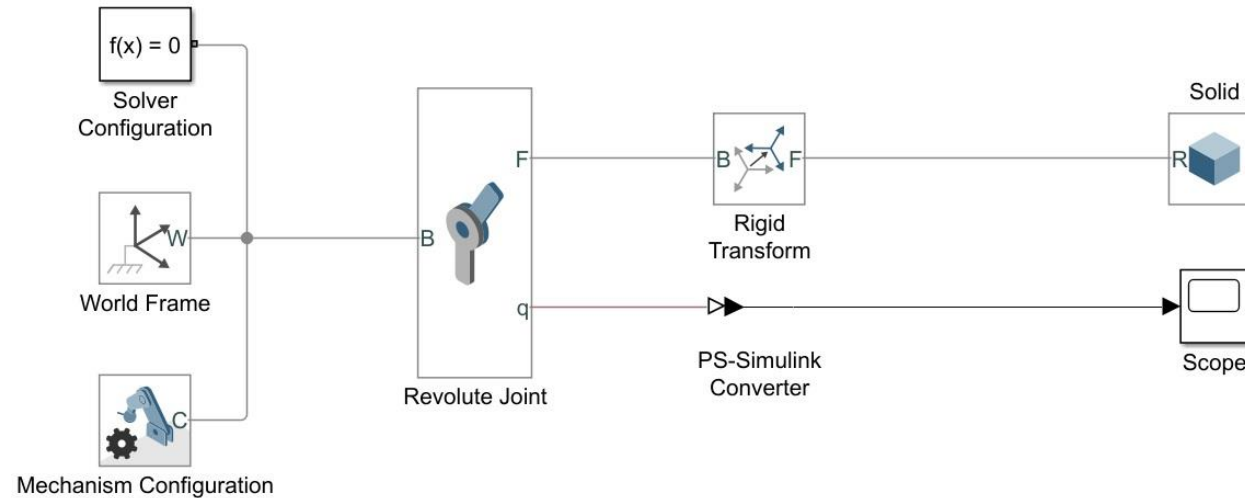
## Introduction – What is Physical Modeling?

- Example 2: This diagram represents what mechanical system?



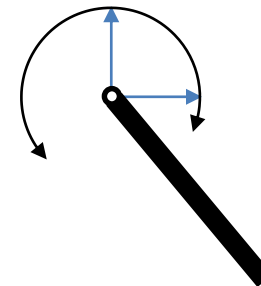
# Introduction – What is Physical Modeling?

- The **physical model** of the same system offers a lot more information.



- This model contains:

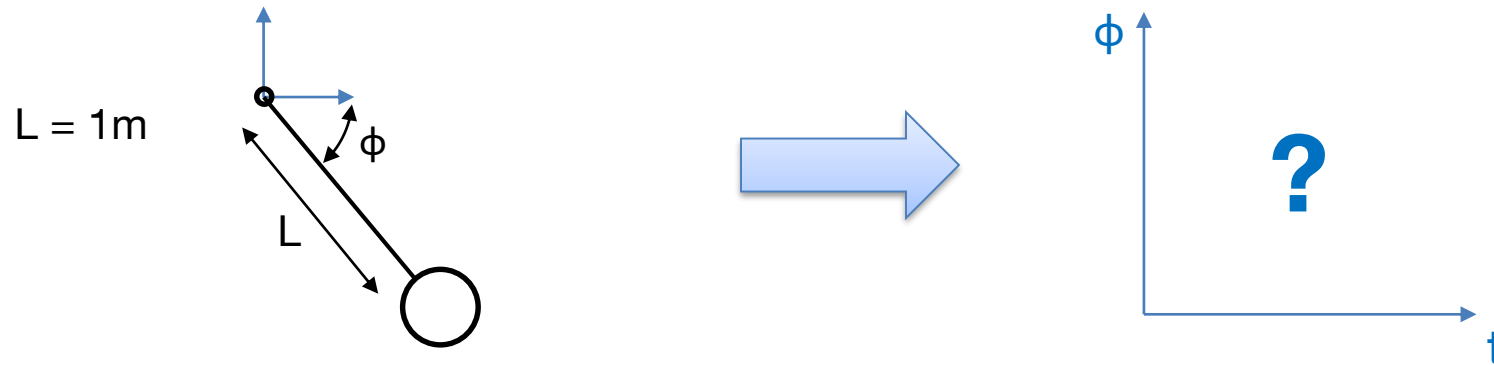
- Body
- Revolute Joint
- Coordinate Frame
- ...



# Introduction – What is Physical Modeling?

- How to **model** this pendulum using **ordinary methods**?

**Goal:** Calculate angle over time

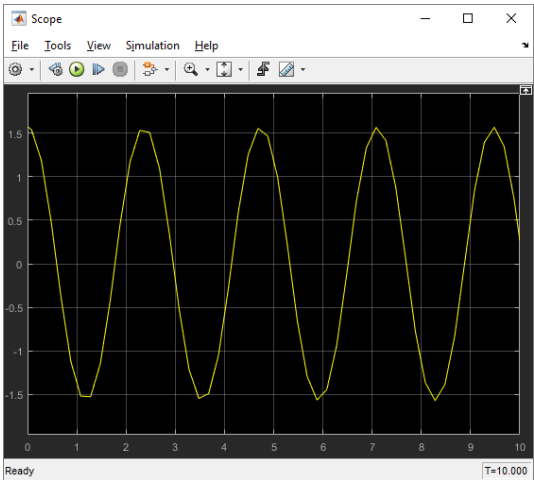
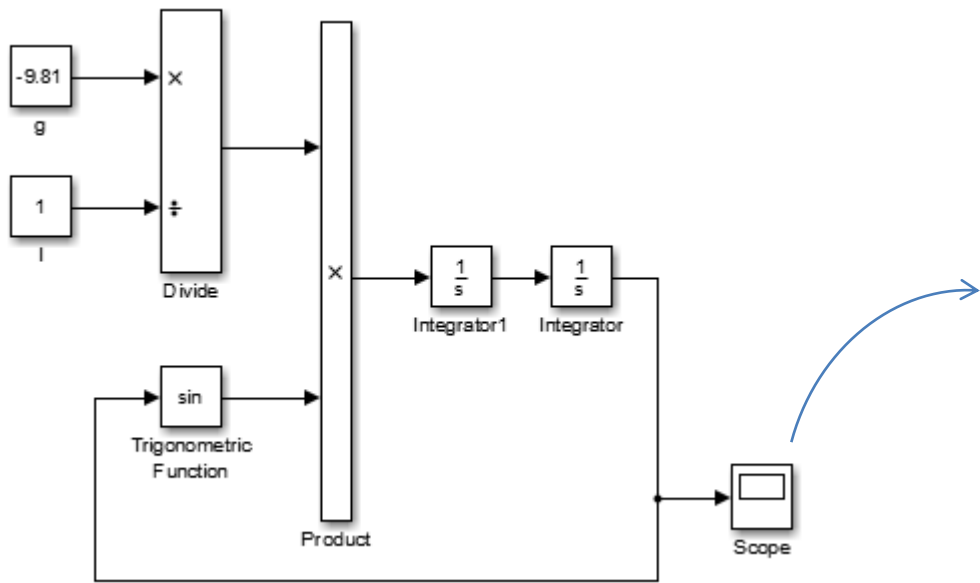


- Differential equation describing system behaviour:

$$\ddot{\phi}(t) + \frac{g}{L} \cdot \sin(\phi(t)) = 0$$

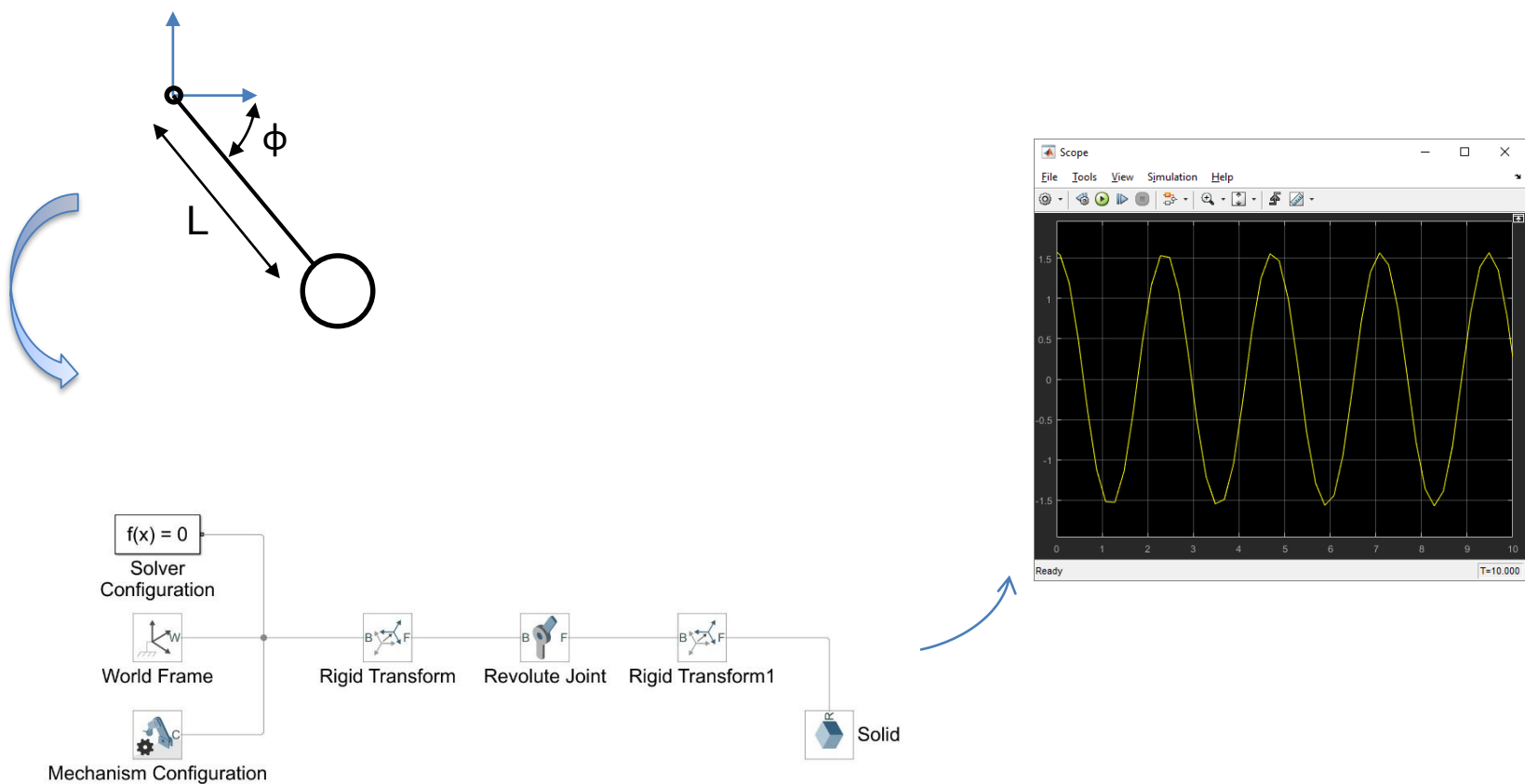
# Introduction – What is Physical Modeling?

- Implementing a Simulink diagram



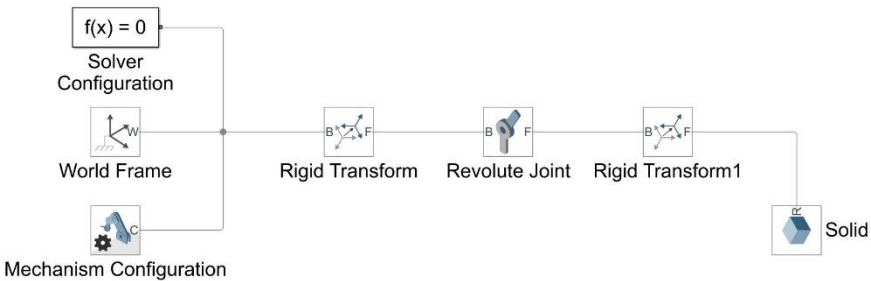
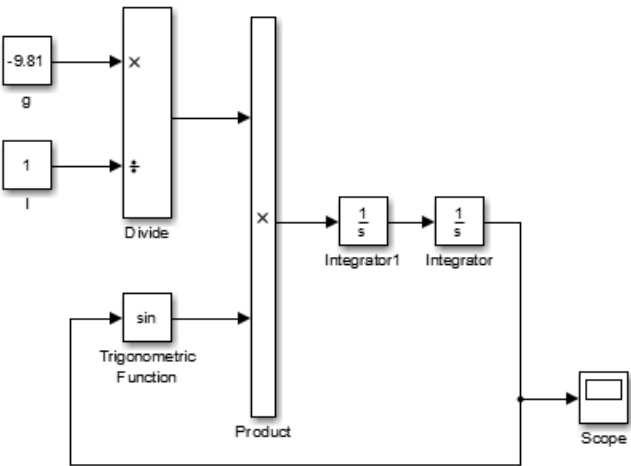
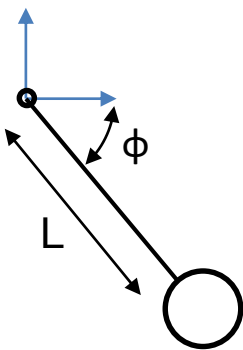
# Introduction – What is Physical Modeling?

- How to **model** the same system using **Physical Modeling (Simscape Multibody)**:



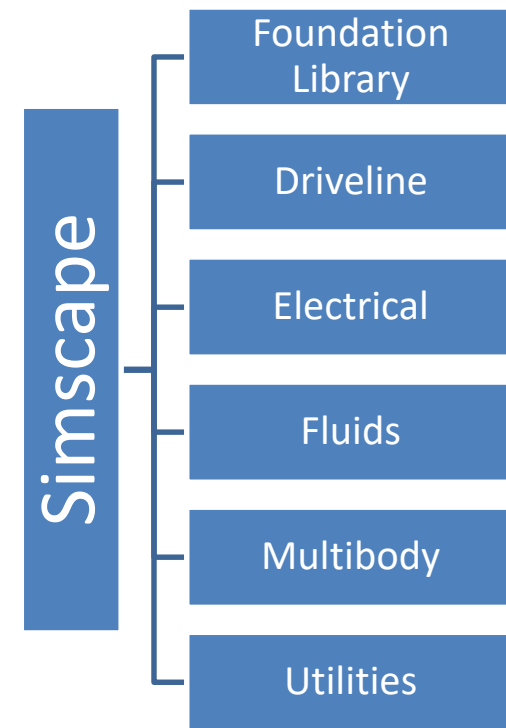
# Introduction – What is Physical Modeling?

- Comparing both models



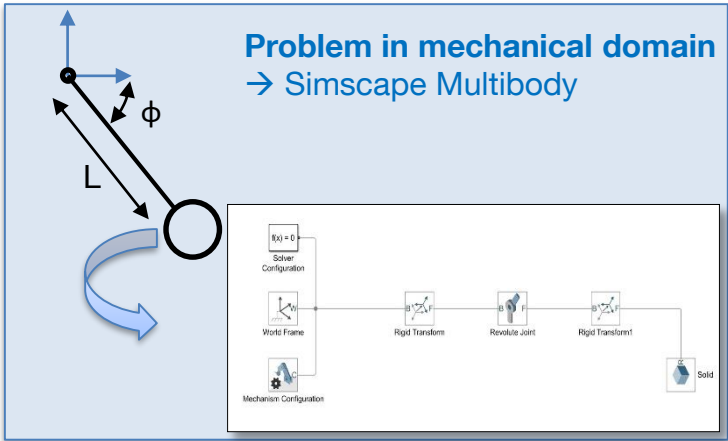
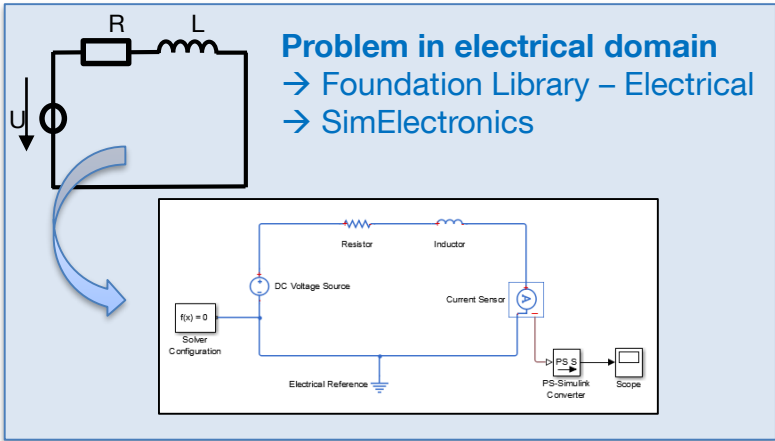
## Introduction – Simscape Toolbox

- **Simscape Toolbox** is useful for **modeling and simulating physical systems** within the Simulink environment.
- Predefined blocksets in the **Foundation Library** for several physical domains: electrical, mechanical, thermal, ...
- **Multi-domain** physical modeling
- Further libraries with predefined blocksets fitted for certain physical domains:
  - Simscape Driveline
  - Simscape Electronics
  - Simscape Fluids
  - Simscape Multibody
  - Simscape Power Systems



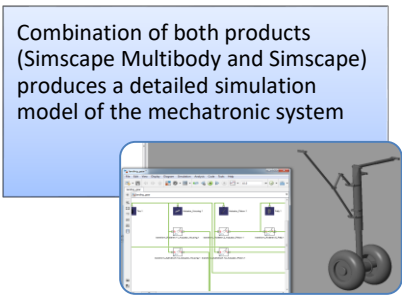
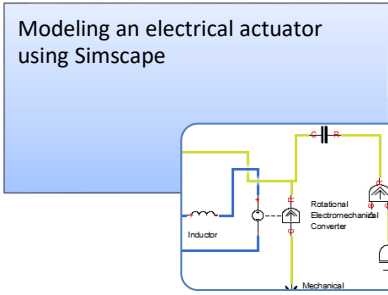
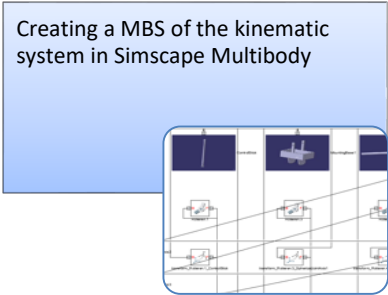
# Introduction – Simscape Toolbox

- Use toolboxes that **suit your problem and it's physical domain.**



- Combine** models that were built with different toolboxes:

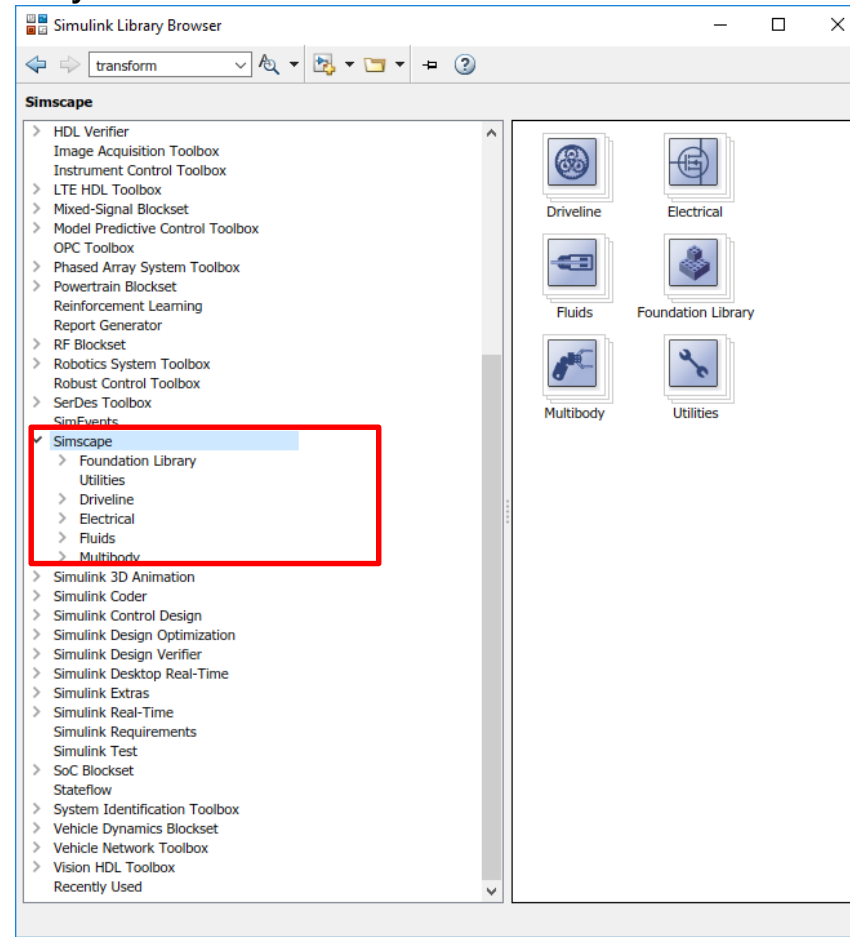
Example:





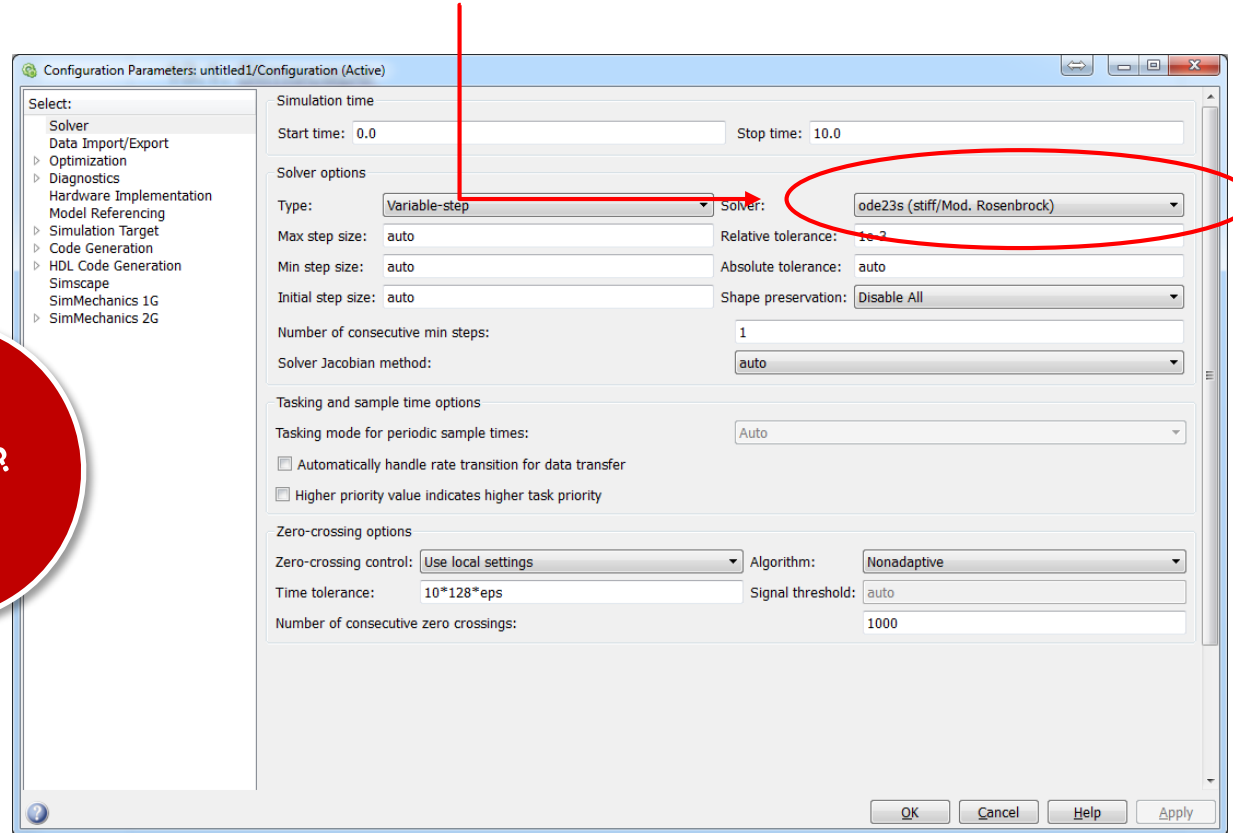
# Introduction – Simscape Toolbox

- Find the Simscape Library and it's toolboxes:

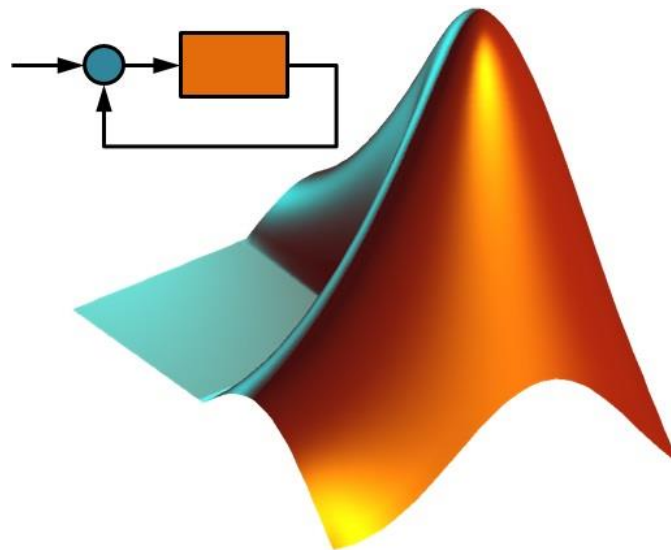


# Introduction – Simscape Toolbox

- Generally stiff solvers (*ending with a s*) are performing much better at physical problems. To set solver settings press CTRL+E in diagram window:



## 2. Multibody Simulation using Simscape Multibody



# Multibody Simulation using SimMechanics

- What is Multibody-Simulation (MBS)?
  - Numerical simulation
  - Composition of **rigid bodies** that are interconnected via **joints** (kinematic constraints)
  - Perform **motion analysis** and calculate forces
  
- Market Overview:
  - **SimMechanics (Simscape Multibody)** (MathWorks)
  - SIMPACK (Dassault Systèmes)
  - Multiphysics (COMSOL)
  - Multibody Dynamics

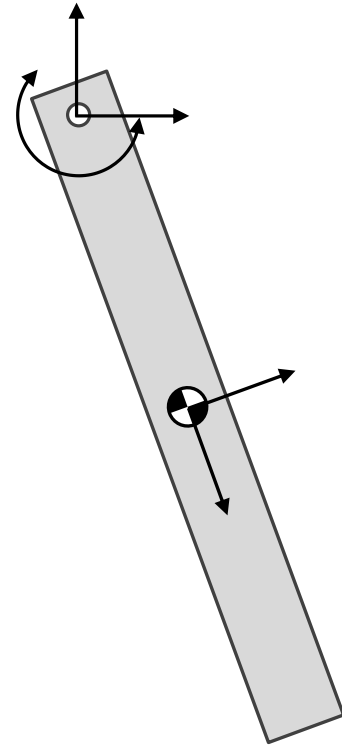
# Multibody Simulation using Simscape Multibody

- What is **Simscape Multibody**
  - **Toolbox of Simscape** that provides a multibody simulation environment for 3D mechanical systems
  - **Model-Based Design** of MBS models
  - First & **Second Generation**
- **Advantages** of Simscape Multibody
  - MBS-Tool **inside** of the MathWorks world
  - Use Simscape Multibody blocks in the Simulink diagram environment
  - **Add electrical, hydraulic and pneumatic components** to your mechanical model (Simscape)
  - Easy 3D visualization of the system dynamics via *Mechanics Explorer*

# Multibody Simulation using Simscape Multibody

## Components of a classical MBS model:

- **Solids** with a defined mass, inertia, center of gravity, ...
- **Joints** to constrain relative motion
- **Coordinate Frames** for positions and orientations



# Multibody Simulation using Simscape Multibody – Preparing the Model

- Any Simscape Multibody model requires the following blocks:

- Solver Configuration**

One block per physical network is needed.

*Simulink Library – Simscape – Utilities*

- World Frame**

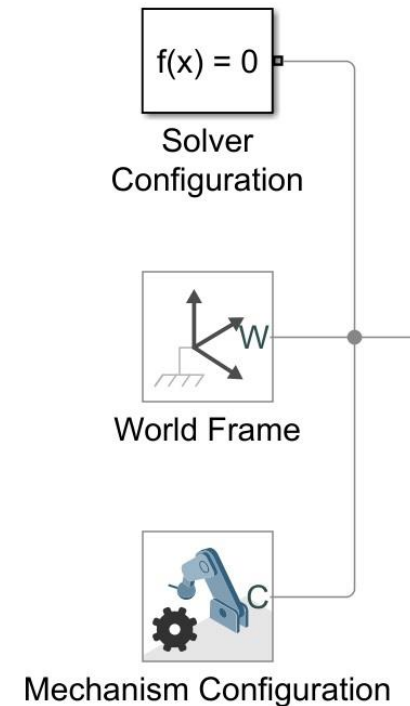
**Fixed reference frame for the mechanism**

*Simulink Library – Simscape – Multibody – Frames and Transforms*

- Mechanism Configuration**

Mainly for setting direction and units of gravity

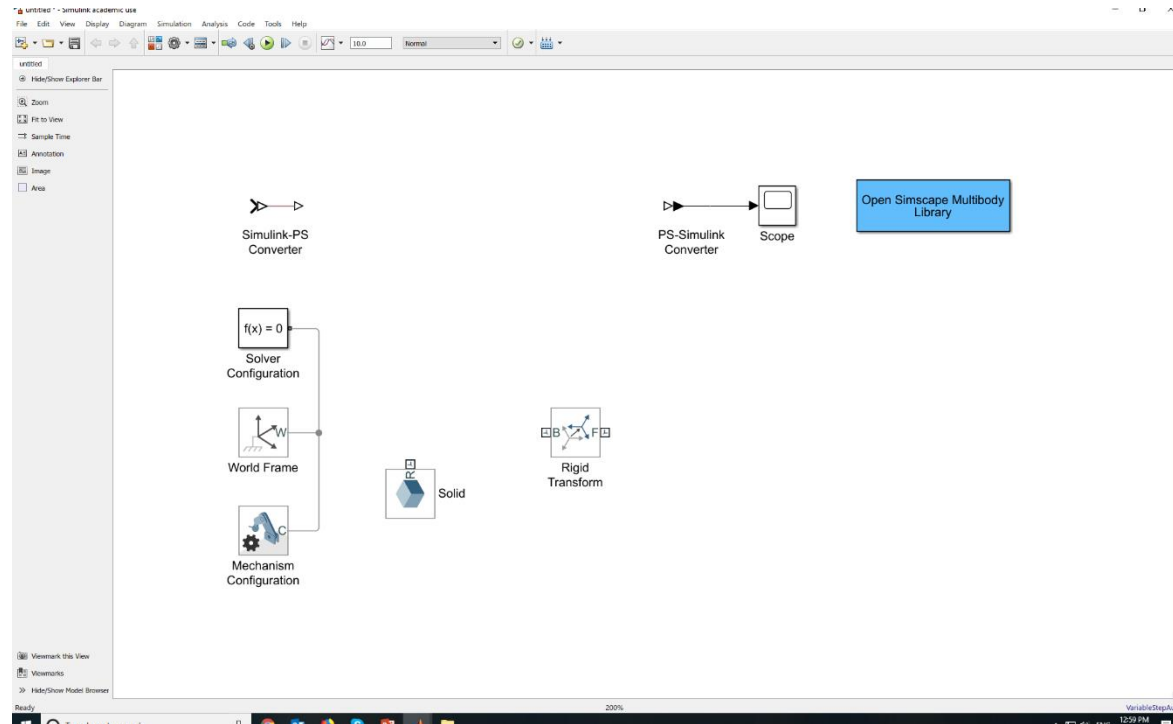
*Simulink Library – Simscape – Simscape Multibody – Utilities*



# Multibody Simulation using Simscape Multibody – Preparing the Model

- Or use the `smnew` command to open a **prepared Simscape Multibody model**:

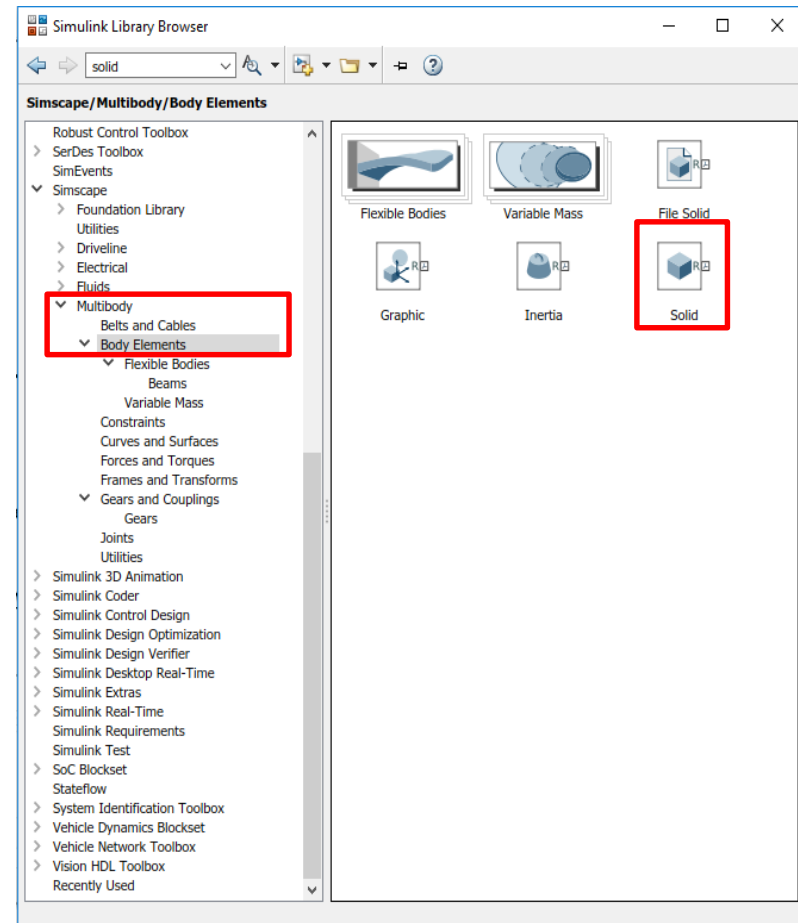
```
>> smnew
```





# Multibody Simulation using Simscape Multibody – Defining Solids

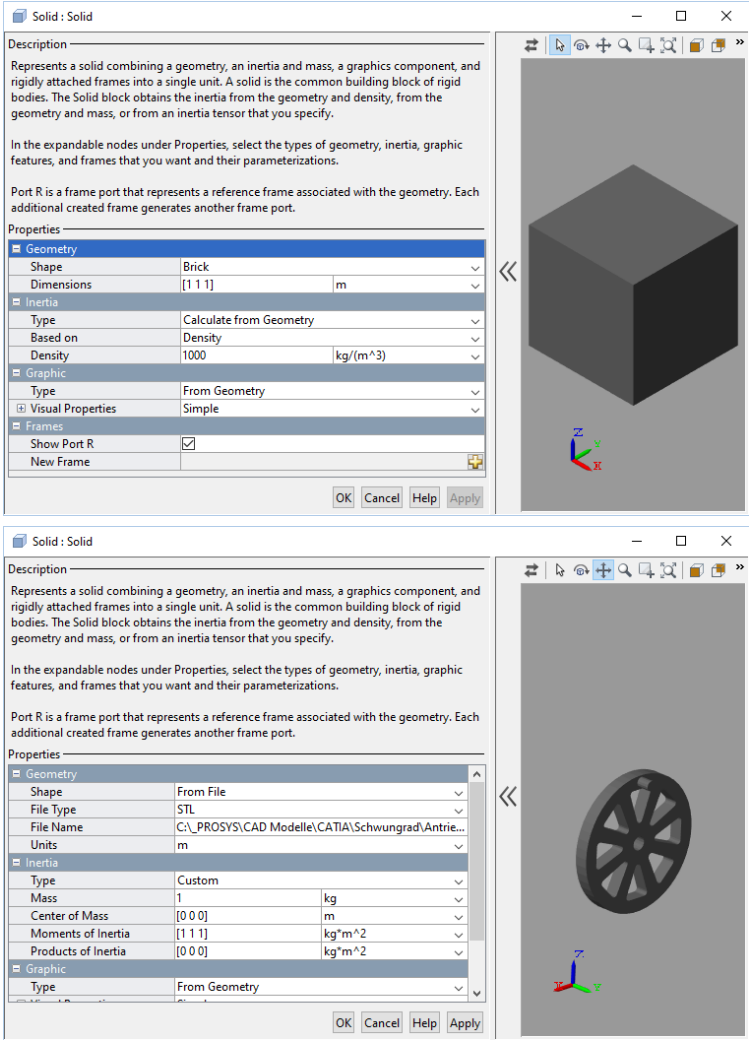
- *Solid* blocks represent **rigid bodies** with a specific mass, inertia and geometry in a multibody simulation.
- Find the *Solid* block:  
*Simscape > Multibody > Body Elements*
- Drag and drop a *Solid* block for each body in your mechanical system to the Simulink diagram.
- Each *Solid* block contains *one coordinate frame*:



# Multibody Simulation using SimMechanics – Defining Solids

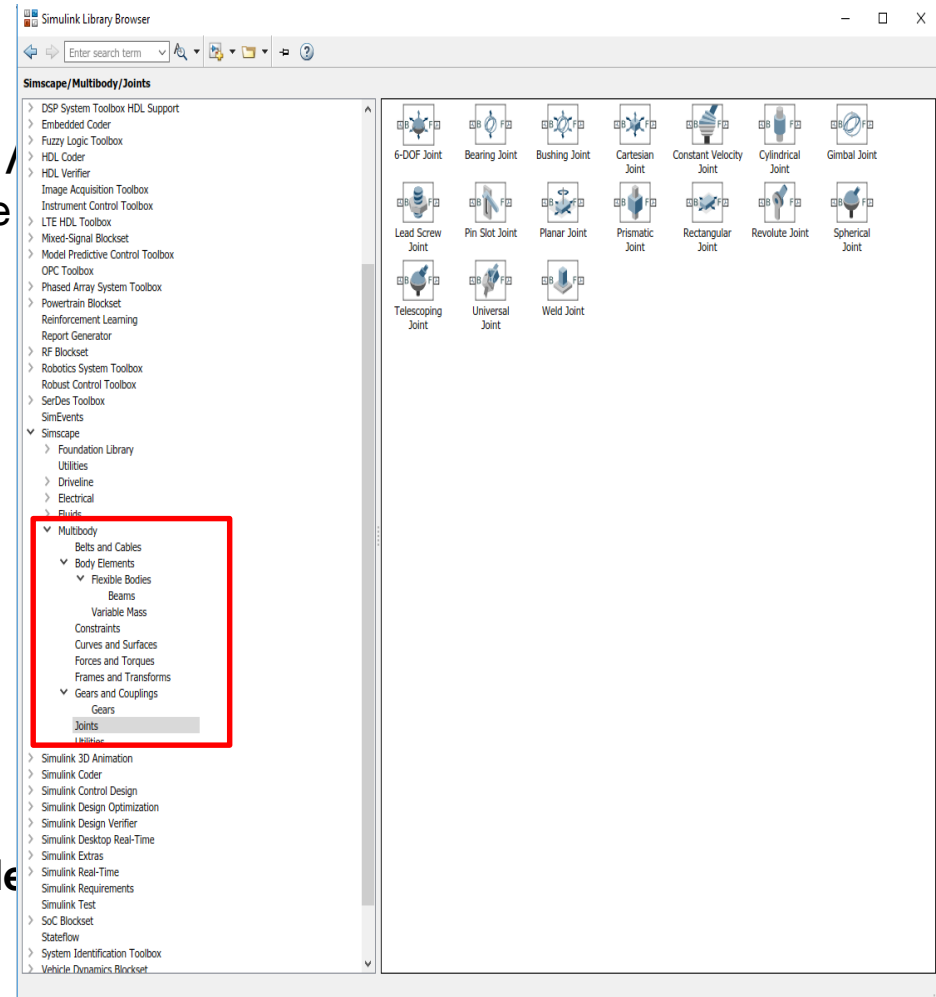
There are various ways to define solids:

- Geometry:
  - Predefined Shapes:
    - Simple geometries using predefined shapes (Brick, Cylinder, Sphere, ...).
    - Only parameters regarding dimensions must be entered.
    - Advantage: Inertia can be calculated from geometry.
  - From File:
    - Shapes can be easily defined using STL or STEP files.
    - Advantage: Very simple import of complex shapes.
- Inertia:
  - Calculated from Geometry:
    - Only available if a predefined Geometry Shape is used.
    - Inertia is calculated automatically based on a given density.
  - Point Mass:
    - Entered mass is positioned in the part's origin.
  - Custom:
    - Besides the mass itself, information about the CG or inertia tensor is required.



# Multibody Simulation using Simscape Multibody – Defining Joints

- Joint blocks are used to connect solids, respectively their coordinate frames to each other. They enable **translational and/or rotational degrees of freedom** to these connections.
- Joints represent **frictionless** connections!
- Find joints:  
*Simscape > Multibody > Joints*  
 Drag and drop a *Joint* block for each connection in your mechanical system to the Simulink diagram.
- Each *Joint* block contains **two** coordinate frames. **The z-axis plays an important role**

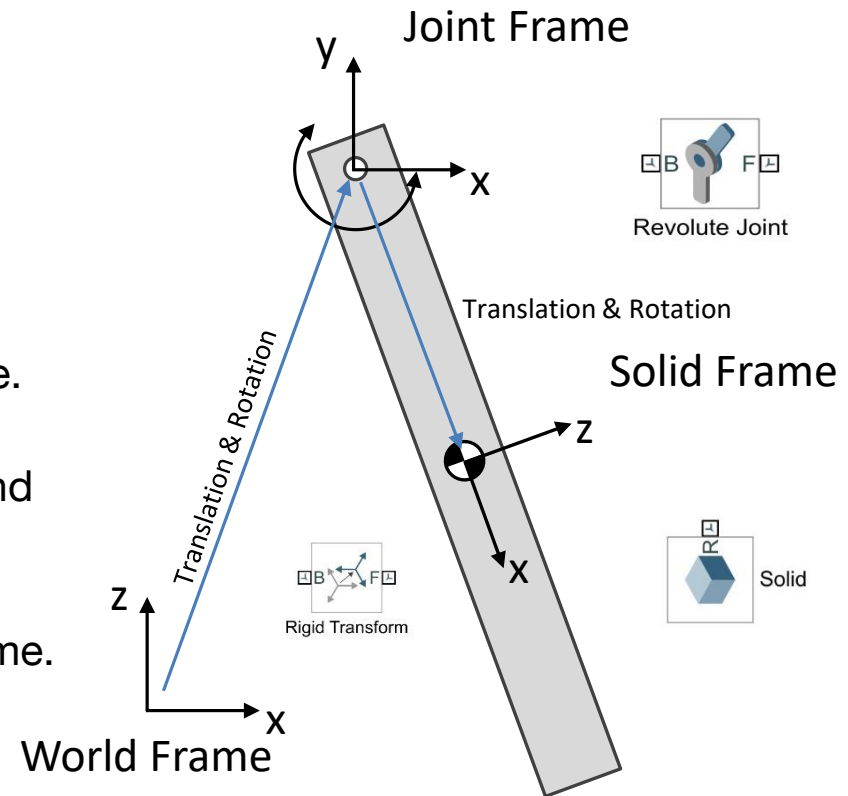


# Multibody Simulation using Simscape Multibody – Defining Coordinate Frames

- Coordinate frames can be copied, moved and rotated using the *Rigid Transform* block. This is required for positioning joints and solids.
- Find *Rigid Transform* blocks:  
*Simscape > Multibody > Frames and Transforms*

## Example: Pendulum

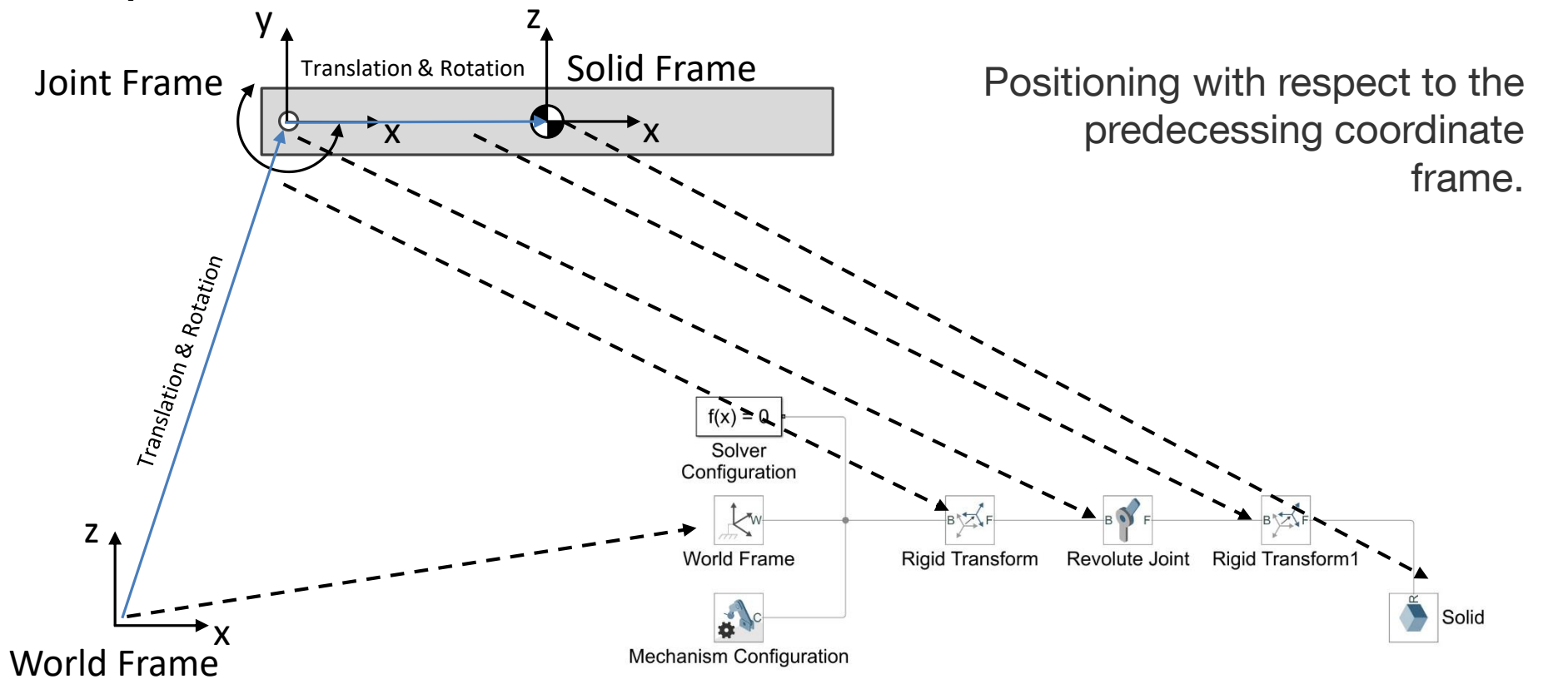
- World frame is copied and **translated**.
- A revolute joint creates a rotational degree of freedom by creating another coordinate frame.
- This coordinate frame is copied, **translated** and **rotated**.
- A solid block is created at this coordinate frame.



# Multibody Simulation using Simscape Multibody – Assembling Mechanisms

Assembling a mechanism means primarily to position all components to each other and link certain solids via joints.

**Example:** Pendulum



# Multibody Simulation using Simscape Multibody – Assembling Mechanisms

Rigid Transform : Rigid Transform

Description

Defines a fixed 3-D rigid transformation between two frames. Two components independently specify the translational and rotational parts of the transformation. Different translations and rotations can be freely combined.

In the expandable nodes under Properties, choose the type and parameters of the two transformation components.

Ports B and F are frame ports that represent the base and follower frames, respectively. The transformation represents the follower frame origin and axis orientation in the base frame.

Properties

Rotation

Method	Standard Axis
Axis	+X
Angle	90

Translation

Method	Cartesian
Offset	[0.5 0 0.5]

OK Cancel

f(x) = 0

Solver Configuration

World Frame

Mechanism Configuration

Rigid Transform : Rigid Transform

Description

Defines a fixed 3-D rigid transformation between two frames. Two components independently specify the translational and rotational parts of the transformation. Different translations and rotations can be freely combined.

In the expandable nodes under Properties, choose the type and parameters of the two transformation components.

Ports B and F are frame ports that represent the base and follower frames, respectively. The transformation represents the follower frame origin and axis orientation in the base frame.

Properties

Rotation

Method	Standard Axis
Axis	+X
Angle	-90 deg

Translation

Method	Cartesian
Offset	[0.40 0 0] m

OK Cancel Help Apply

Solid

# Multibody Simulation using Simscape Multibody – Assembling Mechanisms

Solid : Solid

Description

Represents a solid combining a geometry, an inertia and mass, and a graphics component into a single unit. A solid is the common building block of rigid bodies. The Solid block obtains the inertia from the geometry and density, from the geometry and mass, or from an inertia tensor that you specify.

In the expandible nodes under Properties, select the types of geometry, inertia, and graphic features that you want and their parameterizations.

Port R is a frame port that represents a reference frame associated with the geometry.

Properties

Geometry

ShapeBrick

Dimensions[1 0.1 0.1]m

Inertia

TypeCalculate from Geometry

Based onDensity

Density1000kg/(m^3)

Graphic

TypeFrom Geometry

Visual PropertiesSimple

OK

Cancel

Help

Apply

f(x) = 0

Solver Configuration

W

World Frame

C

Mechanism Configuration

Rigid Transform

Revolute Joint

Rigid Transform1

Solid



X

Y

Z

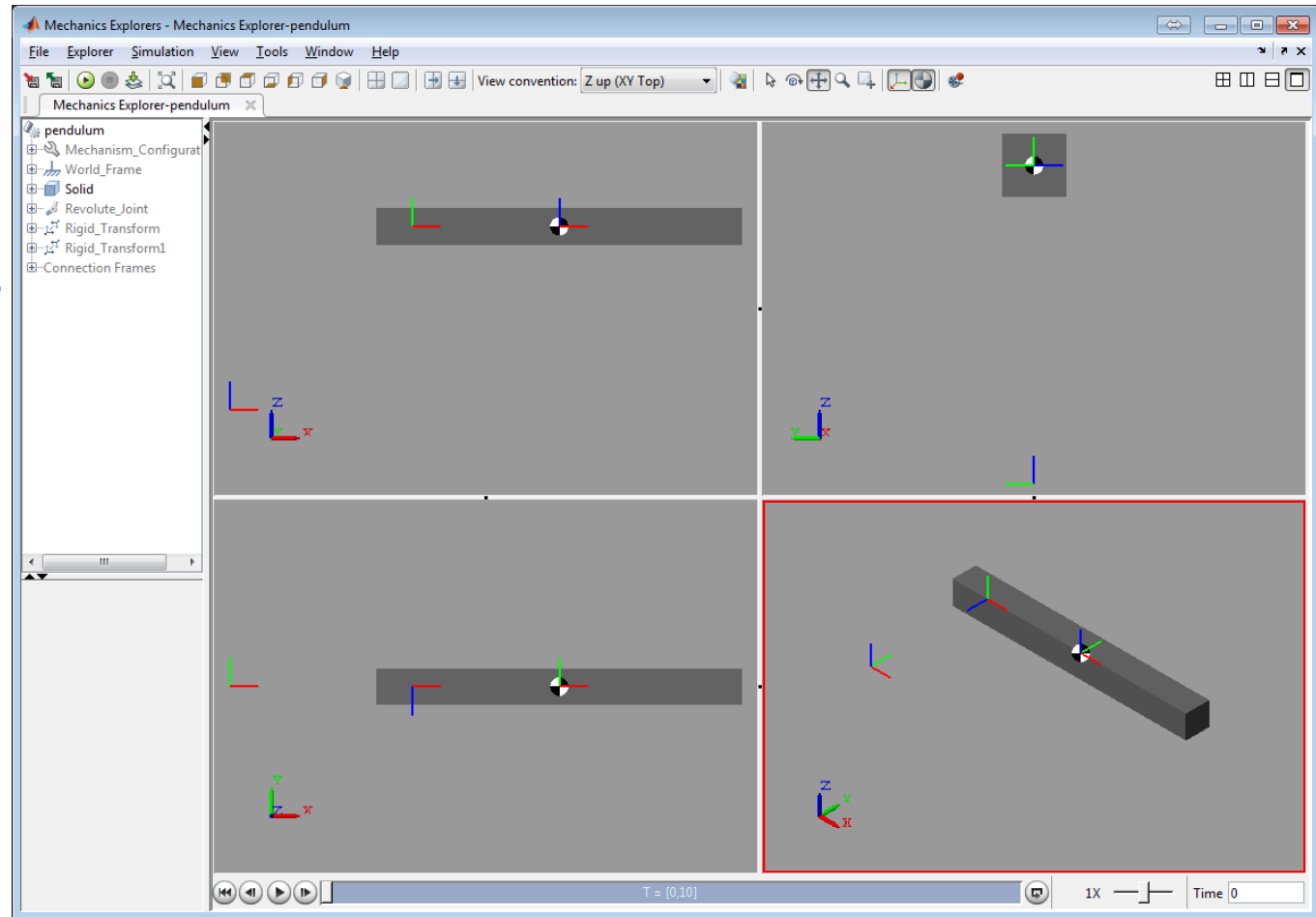
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2019

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Flugsystemdynamik

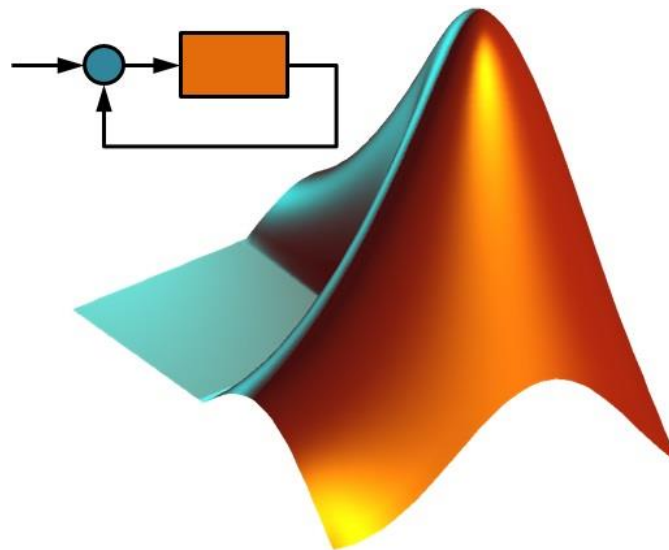
# Multibody Simulation using Simscape Multibody – Visualization

After updating the diagram (CTRL+D) or running the simulation, the mechanism is visualized via the *Mechanics Explorer*.



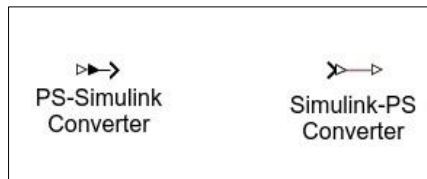


### 3. Configure Joint Settings



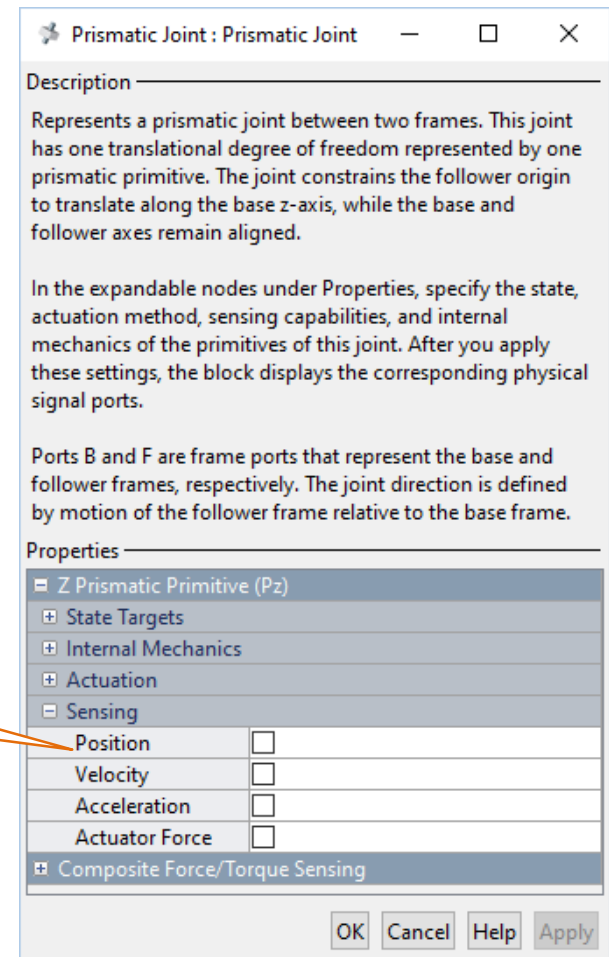
## Configure Joint Settings – Sensing Joint Quantities

- Joints allow to:
  - **measure physical values**
  - actuate their degrees of freedom
- Input values as well as output values, such as velocities or forces, are **physical signals**.
- Converter blocks the PS-Simulink Converter and the Simulink-PS Converter are used to convert signals to the correct format: *Simscape > Utilities*



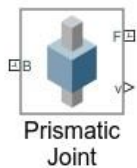
Select variables to measure.

- Possible measurement variables (referred to dof): Position, Velocity, Acceleration, Actuator Force

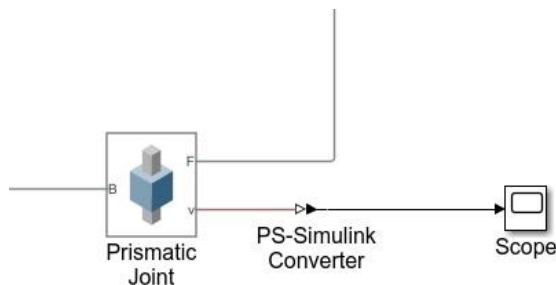


# Configure Joint Settings – Sensing Joint Quantities

- An additional port (PS) appears for every chosen measurement variable:



- Use *PS-Simulink Converter* blocks to process measurements with e.g. *Simulink* blocks:



Prismatic Joint : Prismatic Joint

Description

Represents a prismatic joint between two frames. This joint has one translational degree of freedom represented by one prismatic primitive. The joint constrains the follower origin to translate along the base z-axis, while the base and follower axes remain aligned.

In the expandable nodes under Properties, specify the state, actuation method, sensing capabilities, and internal mechanics of the primitives of this joint. After you apply these settings, the block displays the corresponding physical signal ports.

Ports B and F are frame ports that represent the base and follower frames, respectively. The joint direction is defined by motion of the follower frame relative to the base frame.

Properties

State targets

Internal Mechanics

Actuation

Sensing

Composite Force/Torque Sensing

Position	<input type="checkbox"/>
Velocity	<input checked="" type="checkbox"/>
Acceleration	<input type="checkbox"/>
Actuator Force	<input type="checkbox"/>

OK

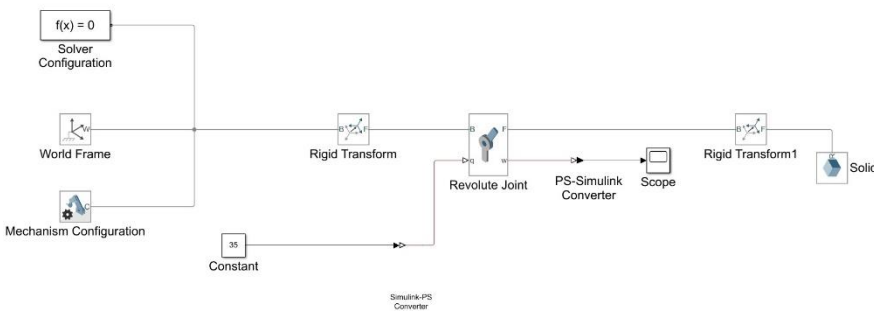
Cancel

Help

Apply

# Configure Joint Settings – Actuating Joints

- Actuating modes:
  - Force / Torque driven: A force / torque is given, corresponding motion is calculated
  - Motion driven: A motion signal is given, corresponding force / torque is calculated
- Force / Torque driven actuation:
  - Input: Force / torque
  - Automatically computed: Motion
  - Example:



Prismatic Joint : PrismaticJoint

Description

Represents a prismatic joint between two frames. This joint has one translational degree of freedom represented by one prismatic primitive. The joint constrains the follower origin to translate along the base z-axis, while the base and follower axes remain aligned.

In the expandable nodes under Properties, specify the state, actuation method, sensing capabilities, and internal mechanics of the primitives of this joint. After you apply these settings, the block displays the corresponding physical signal ports.

Ports B and F are frame ports that represent the base and follower frames, respectively. The joint direction is defined by motion of the follower frame relative to the base frame.

Properties

Z Prismatic Primitive (Pz)

State Targets

Internal Mechanics

Actuation

Force	Provided by Input	▼
Motion	Automatically Computed	▼

Sensing

Composite Force/Torque Sensing

OK

Cancel

Help

Apply

# Configure Joint Settings – Actuating Joints

- Motion driven actuation:
  - Input: Motion signal (position, velocity, acceleration)
  - Automatically computed: Force / torque
  - S-PS block needs specific setting:

Parameters

Units

Input Handling

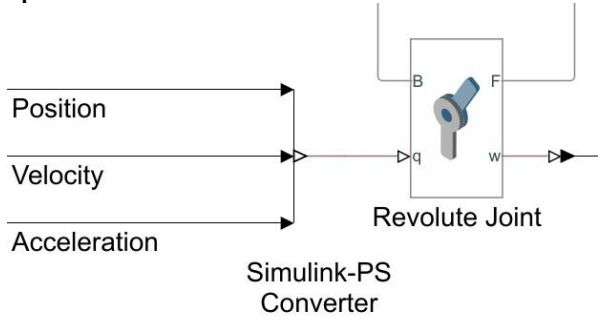
Filtering and derivatives:

Provide input derivative(s)

Input derivatives:

Provide first and second derivatives

- Example:



Revolute Joint : Revolute Joint

Description

Properties

Represents a revolute joint acting between two frames. This joint has one rotational degree of freedom represented by one revolute primitive. The joint constrains the origins of the two frames to be coincident and the z-axes of the base and follower frames to be coincident, while the follower x-axis and y-axis can rotate around the z-axis.

In the expandable nodes under Properties, specify the state, actuation method, sensing capabilities, and internal mechanics of the primitives of this joint. After you apply these settings, the block displays the corresponding physical signal ports.

Ports B and F are frame ports that represent the base and follower frames, respectively. The joint direction is defined by motion of the follower frame relative to the base frame.

Z Revolute Primitive (Rz)

State Targets

Internal Mechanics

Limits

Actuation

Sensing

Composite Force/Torque Sensing

Torque	Automatically Computed	▼
Motion	Provided by Input	▼
Position	<input type="checkbox"/>	
Velocity	<input checked="" type="checkbox"/>	
Acceleration	<input type="checkbox"/>	
Actuator Torque	<input type="checkbox"/>	
Lower-Limit Torque	<input type="checkbox"/>	
Upper-Limit Torque	<input type="checkbox"/>	

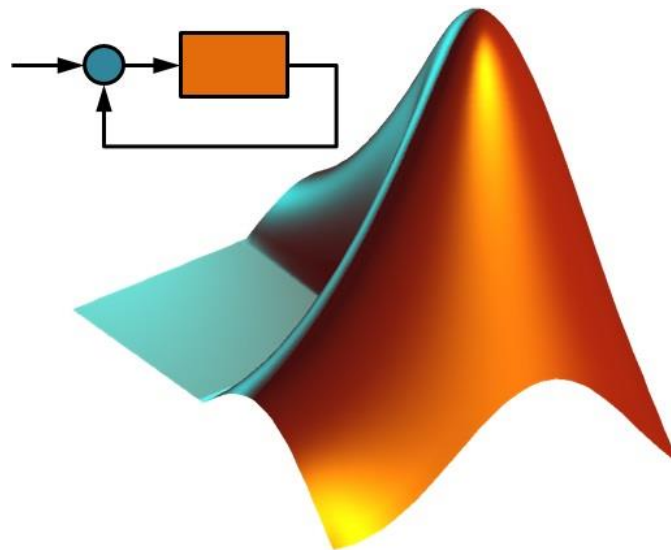
OK

Cancel

Help

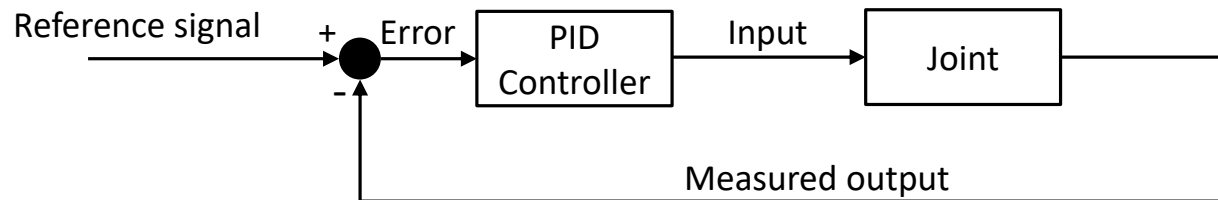
Apply

## 4. Combining Simscape Multibody and Simulink Models



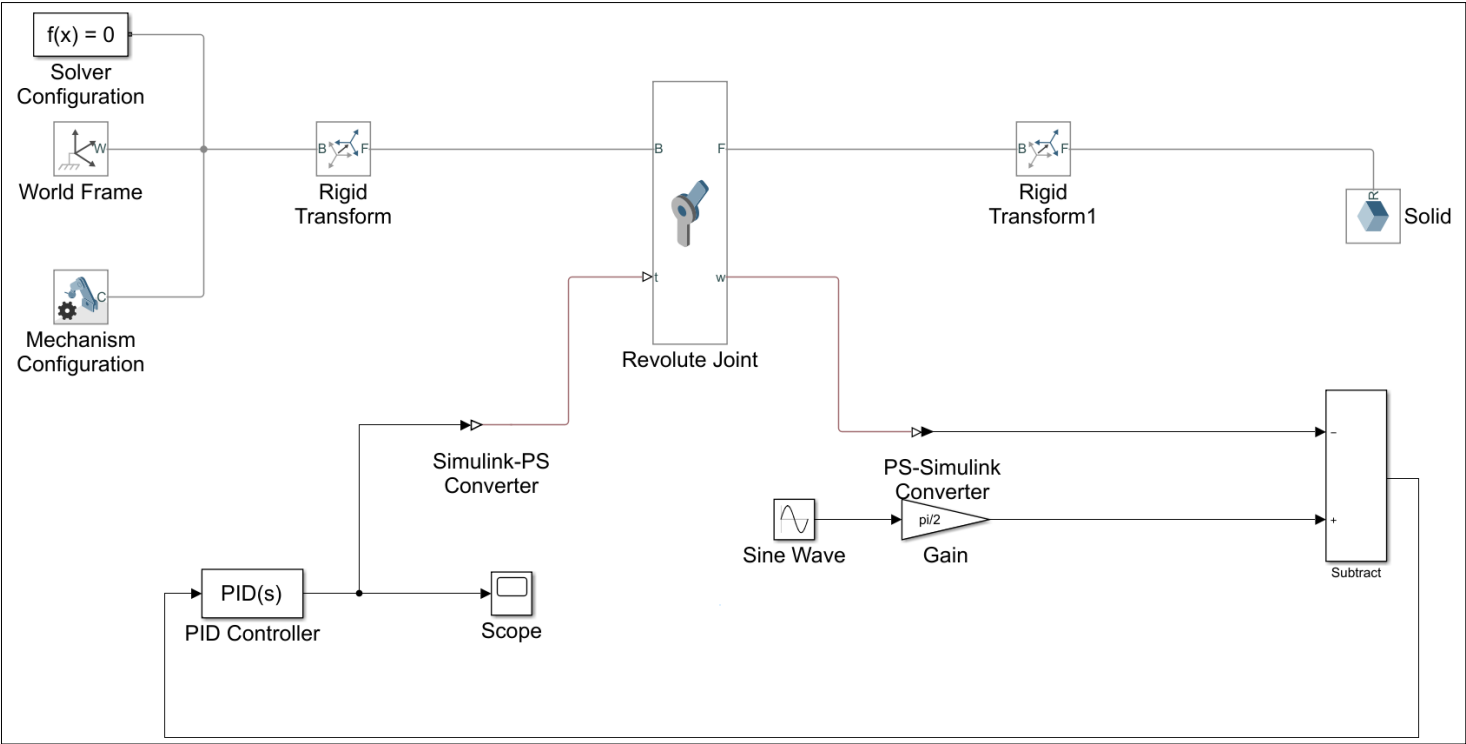
## Combining Simscape Multibody and Simulink Models

- Interface to Simulink: *PS-Simulink* and *Simulink-PS* blocks
- Use **toolboxes that suit your problem**, e.g. Stateflow for logics, Simulink for controllers etc.
- Example: Use PID Controller to actuate joint



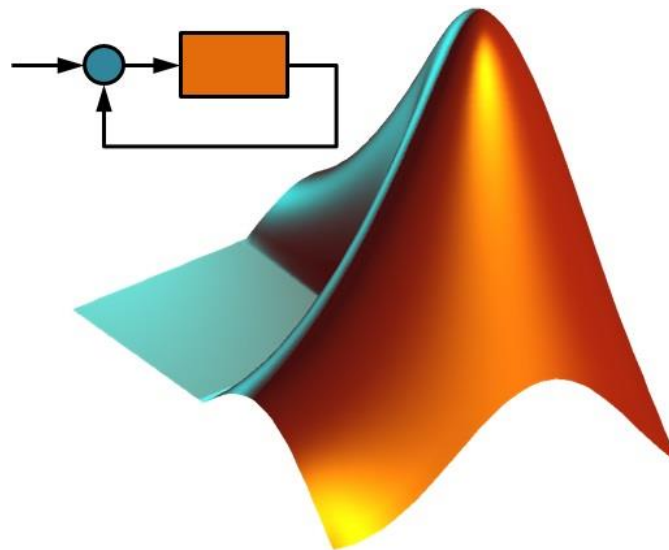
# Combining Simscape Multibody and Simulink Models

Example: *PID Controller* block used to actuate joint





## 5. CAD Import



# Simscape Multibody Interfaces

## Advantages of Interfaces:

- Fast translation of even complex CAD models to Simscape Multibody models
- Reduction of error sources
- Intercommunication of CAD software and Simscape Multibody

## Simscape Multibody Link

- MathWorks offers *Simscape Multibody Link* to export CAD data to Simscape Multibody
- Supported CAD tools: SolidWorks, PTC Creo, Autodesk Inventor
- Steps:
  - Creation of a xml and stl files
  - Generate a Simscape Multibody model from a xml import file using the *smimport* command

```
>> [H,dataFileName] = smimport(xmlFileName)
```

- Missing functionality:
  - Interface is not bidirectional
  - No support for Dassault Systèmes CATIA
  - No direct connection - Indirect way over xml file

## TUM-FSD Interface

- TUM-FSD developed an interface (ProSys) between CAD tools and Simscape Multibody
- Advantages:
  - Bidirectionality: MATLAB can change CAD Parameters
  - Apply MATLAB methods on CAD model (optimization algorithms, sensitivity analysis, ...)
  - Direct communication (no route over external file)
  - Support of CATIA V5

