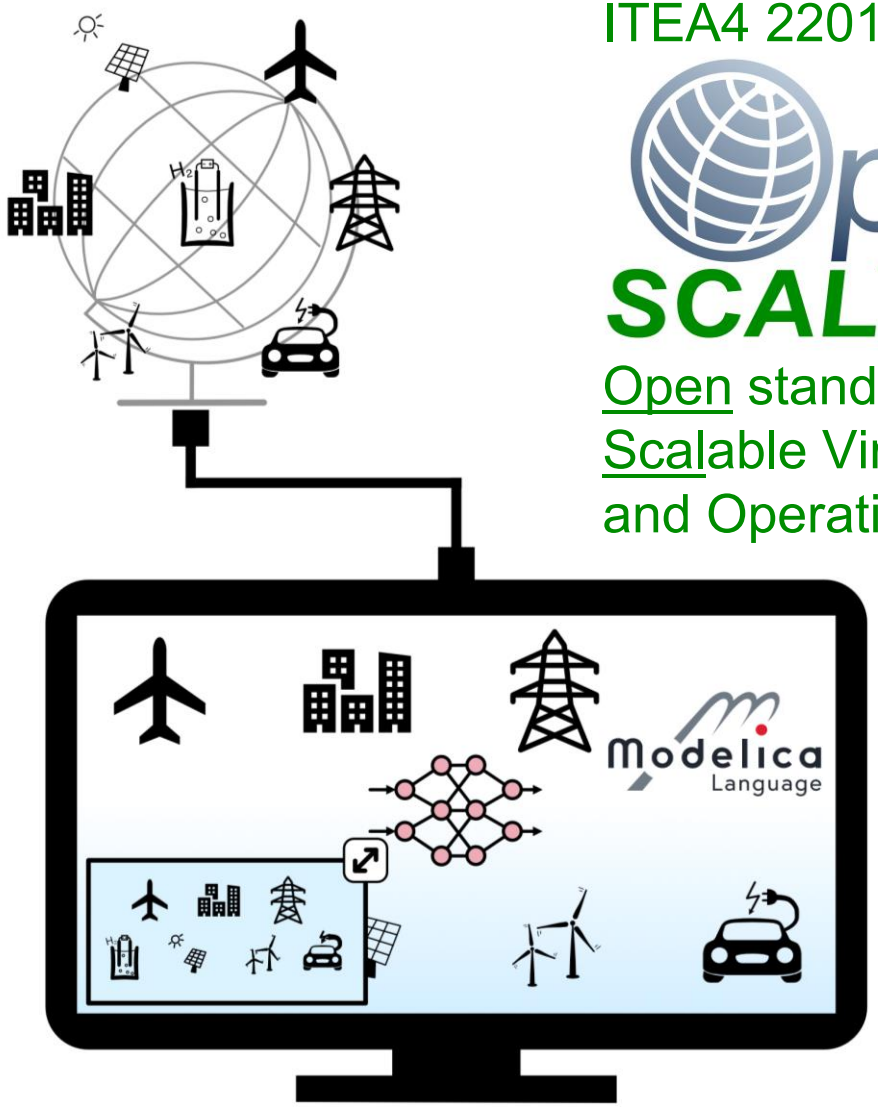
LS-SA: Developing an FMI layered standard for holistic & efficient sensitivity analysis of FMUs

Tobias Thummerer, Hans Olsson, Chen Song, Julia Gundermann, Torsten Blochwitz, Lars Mikelsons

The 16th International Modelica & FMI Conference

Lucerne – Sep. 2025



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Agenda

1 Motivation

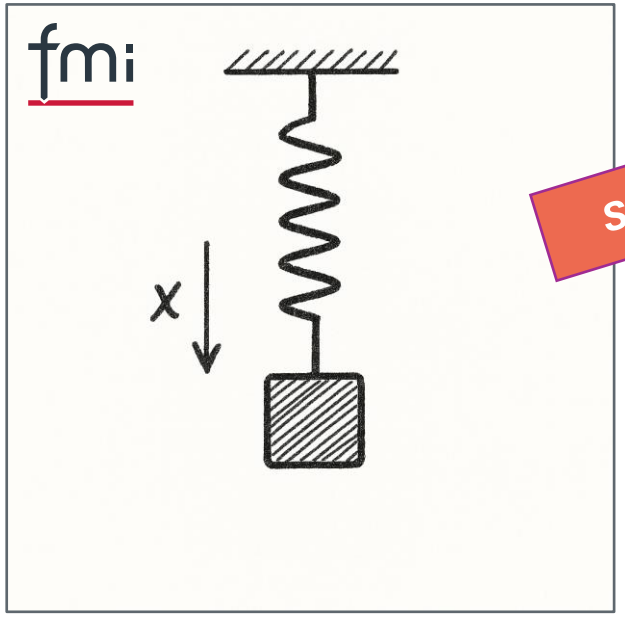
2 Requirements & Solutions

3 Conclusion & Future Work

1 MOTIVATION

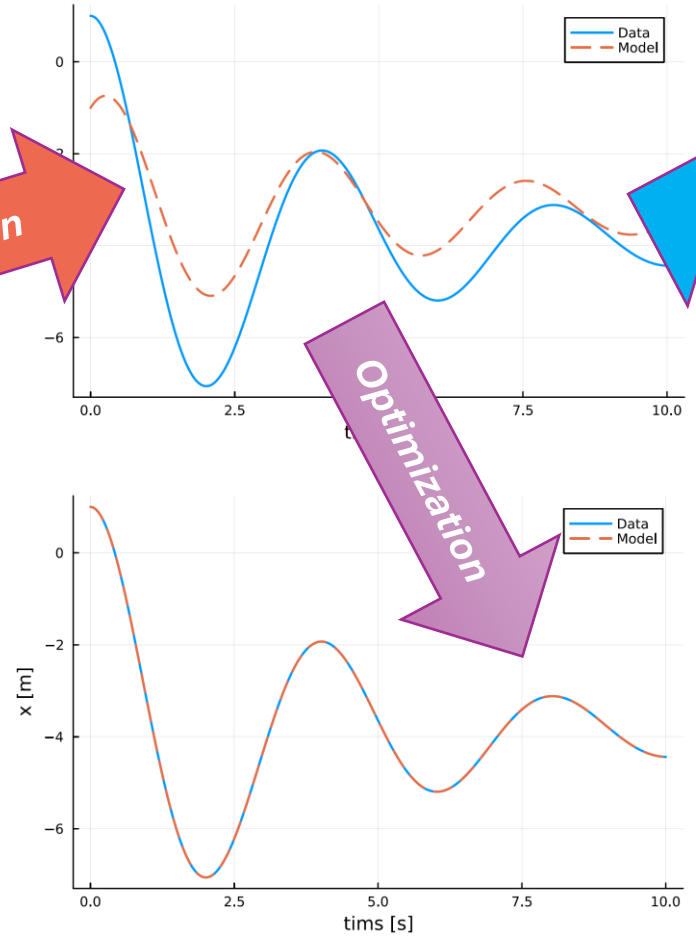
1. Motivation

Gradient-based (Parameter) Optimization



Translational Pendulum
(Model)

Simulation



Measurement



Translational Pendulum
(Real-World System)

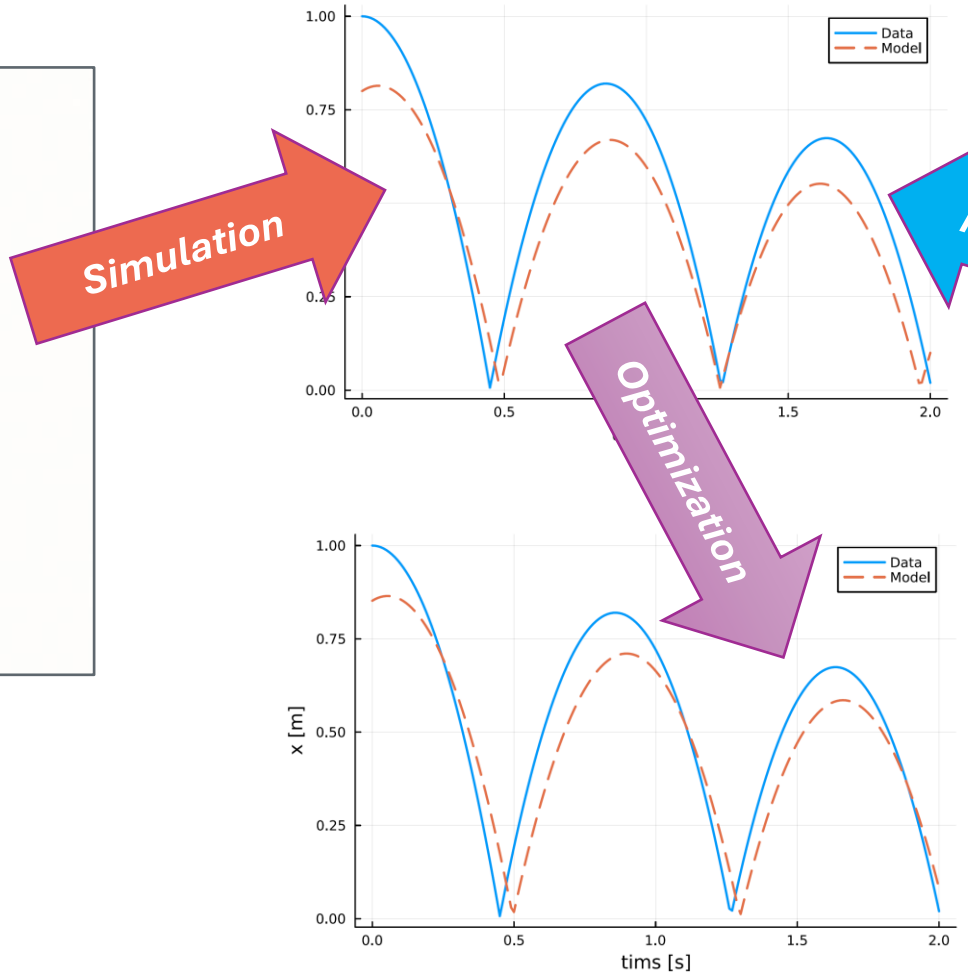
Images of Pendulum:
Generated with the help of AI (ChatGPT).

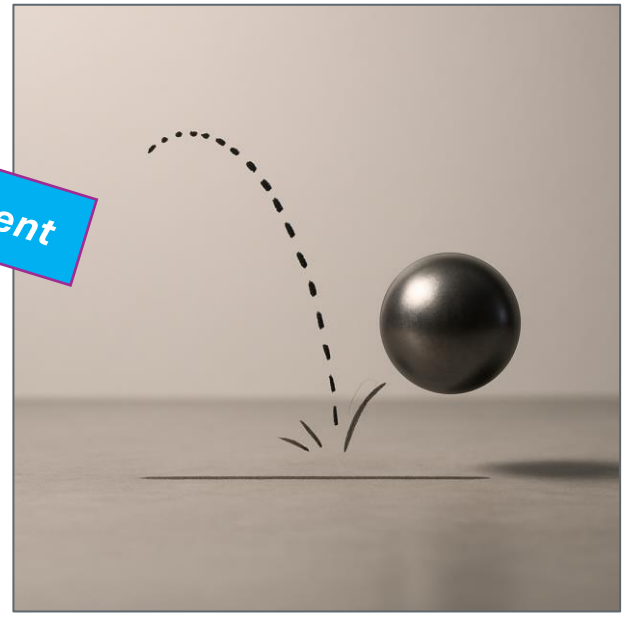
1. Motivation

Gradient-based (Parameter) Optimization



Bouncing Ball
(Model)

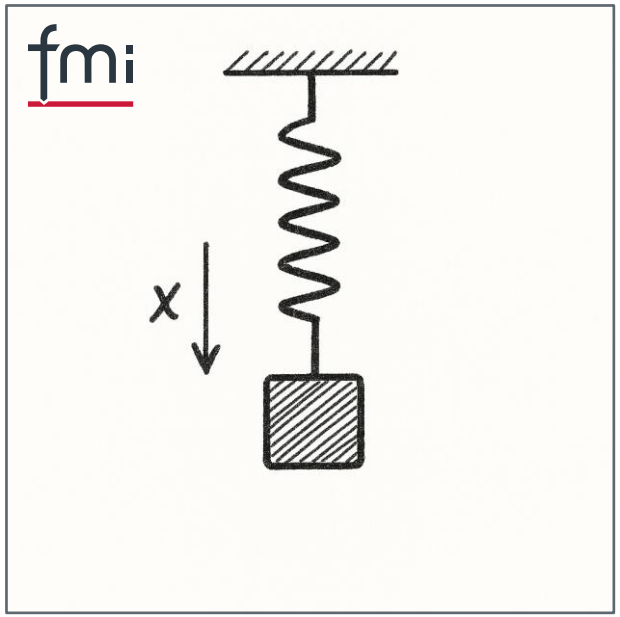




Bouncing Ball
(Real-World System)

Images of Bouncing Ball:
Generated with the help of AI (ChatGPT).

1. Motivation
(Parameter) Optimization



Translational Pendulum

$$\ddot{x} = -g - \frac{c \cdot x}{m} - \frac{d \cdot \dot{x}}{m}$$



Bouncing Ball

$$\ddot{x} = -g$$

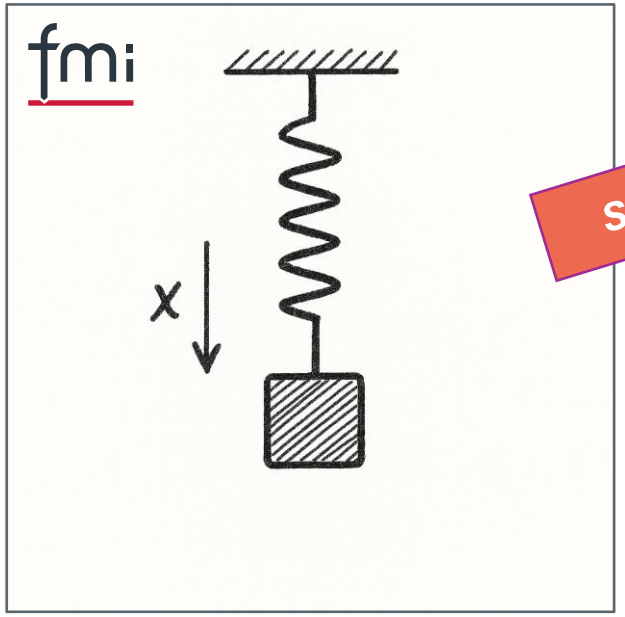
$$z(x) = x$$

$$x(t^+) = -d \cdot x(t^-)$$

Images of Pendulum and Bouncing Ball:
Generated with the help of AI (ChatGPT).

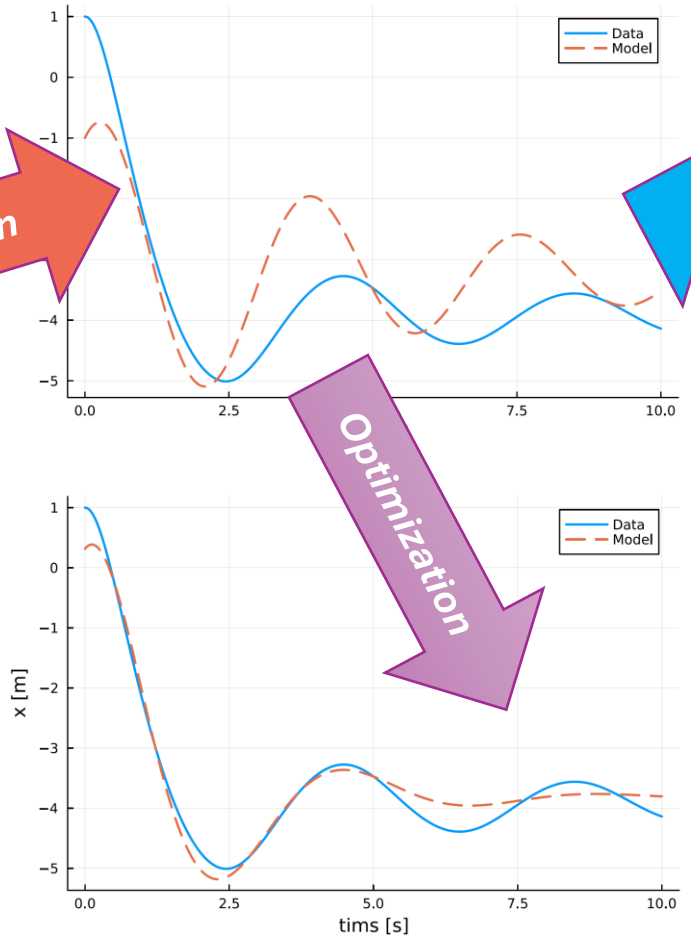
1. Motivation

Hybrid Modeling with FMI



Translational Pendulum
(Model)

Simulation



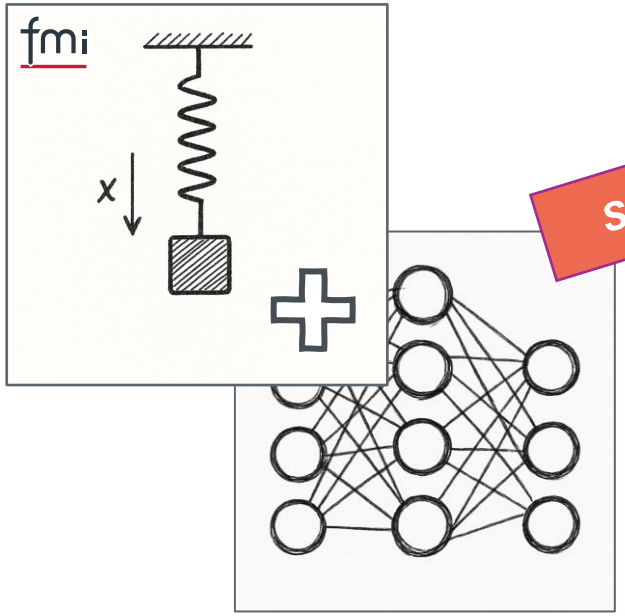
Measurement



Translational Pendulum
(Real-World System)

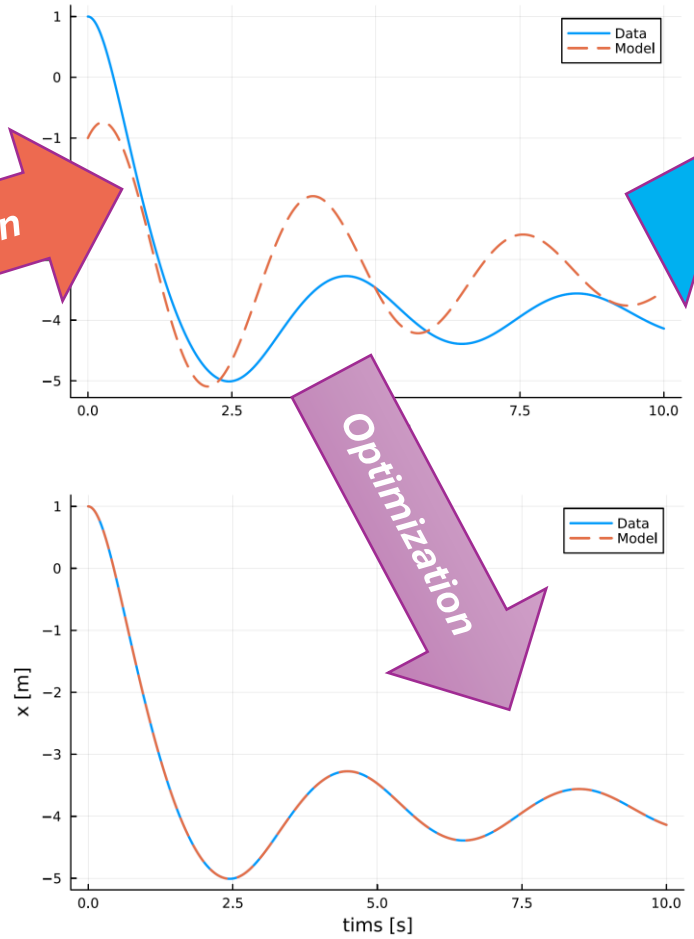
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Hybrid Modeling with FMI

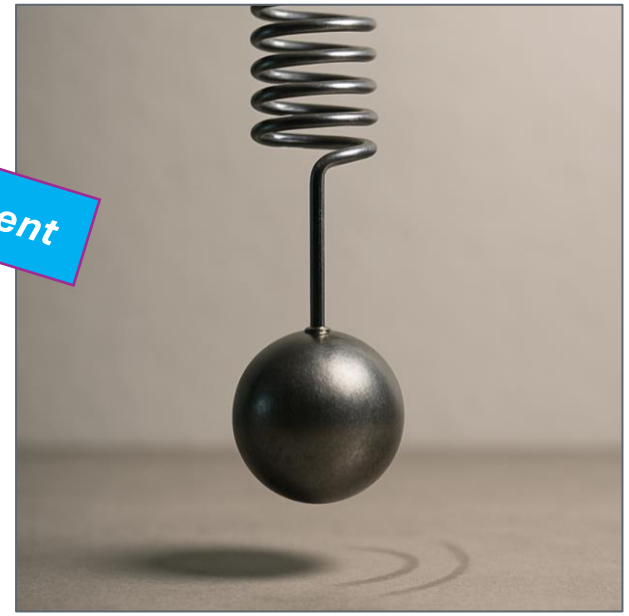


Translational Pendulum
(Neural FMU)

Simulation



Measurement



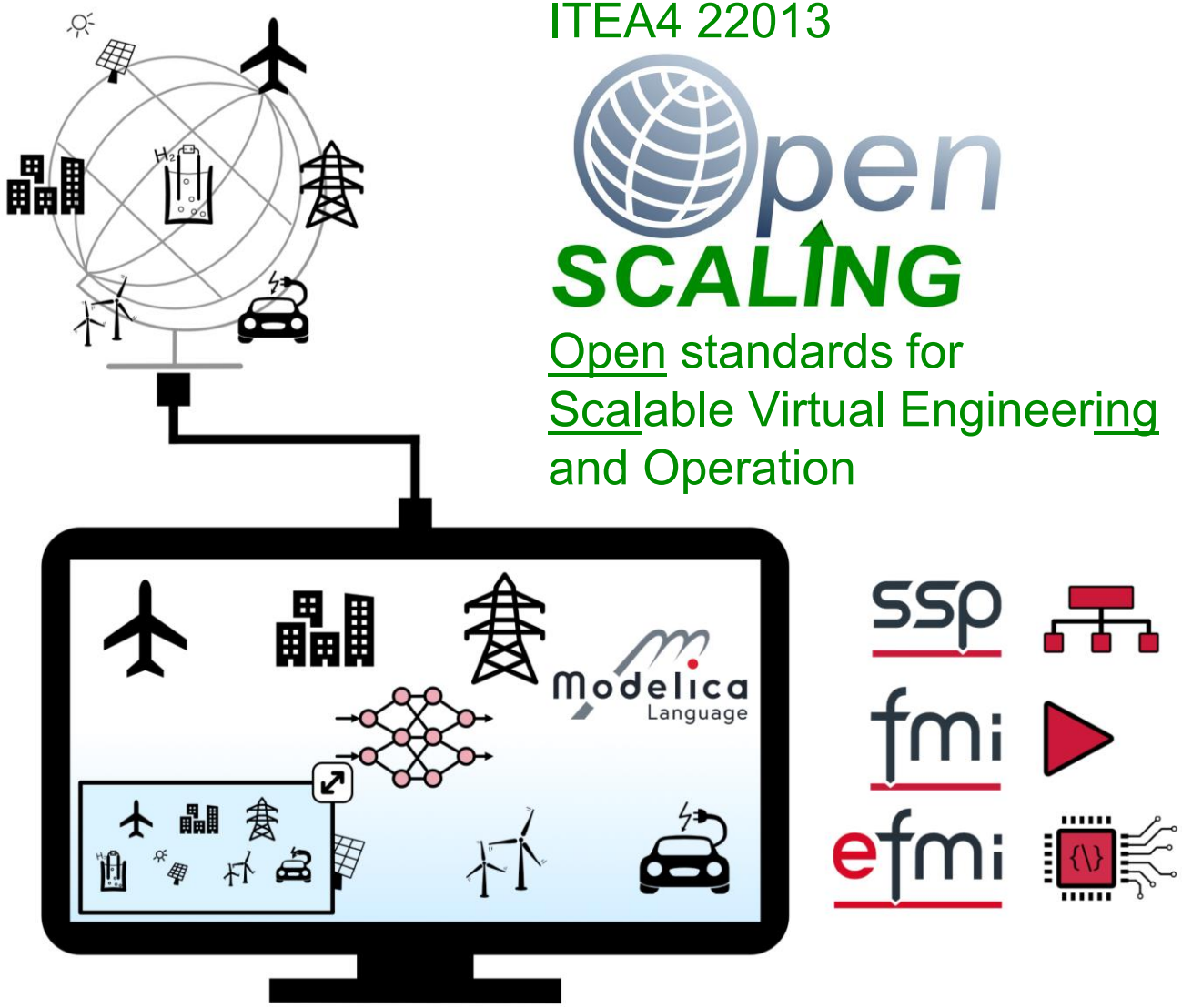
Translational Pendulum
(Real-World System)

Neural FMUs:
2021: Tobias Thummerer Josef Kircher Lars Mikelsons. "NeuralFMU: Towards Structural Integration of FMUs into Neural Networks.„ *Modelica Conferences*. 2021.

Br(e)aking the boundaries of physical simulation models: Neural Functional Mock-up Units for Modeling the Automotive Braking System

Tobias Thummerer, Fabian Jarmolowitz,
Daniel Sommer, Lars Mikelsons

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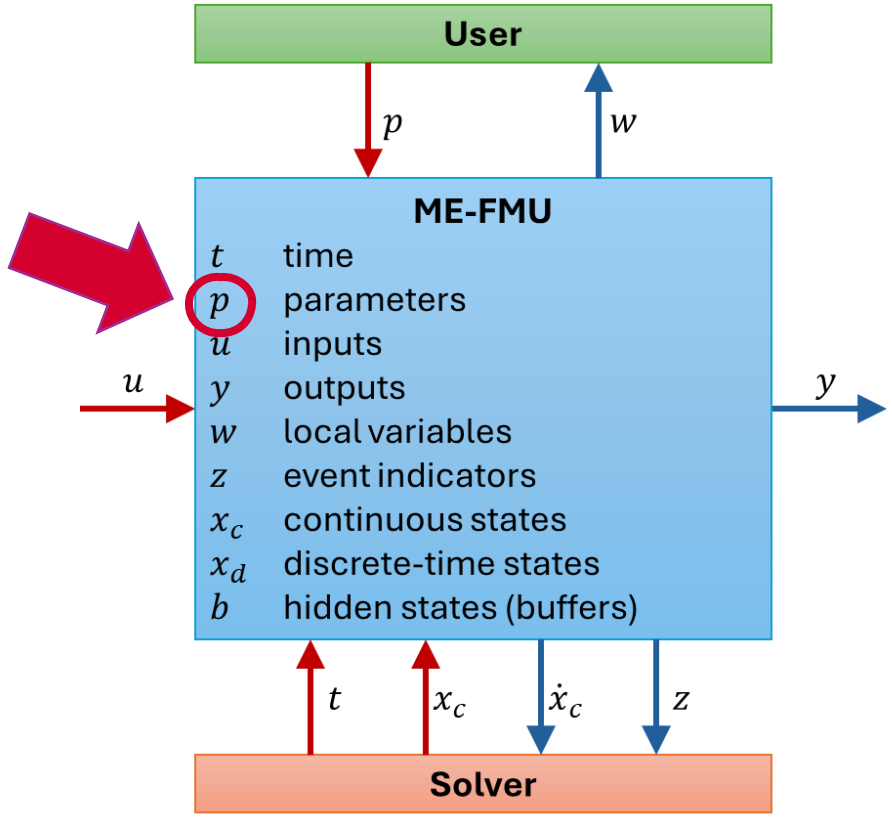
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2

REQUIRMENTS & SOLUTIONS

2. Requirements & Solutions

"Internal" Parameters = SA for Parameters *inside* the FMU (e.g. model calibration)



SA* for event ME-FMUs … in 60 seconds

solve

1. Parameters influence the right-hand side → $\frac{\partial \dot{x}}{\partial p}$
2. States influence the right-hand side → $\frac{\partial \dot{x}}{\partial x}$
3. Right-hand side gets integrated to state, which again influences the right-hand side
   → not our (FMI) problem

identify

4. Event time depends on event indicators
   → not our (FMI) problem
5. Event indicator depends on parameters → $\frac{\partial z}{\partial p}$
6. Event indicator depends on states → $\frac{\partial z}{\partial x}$

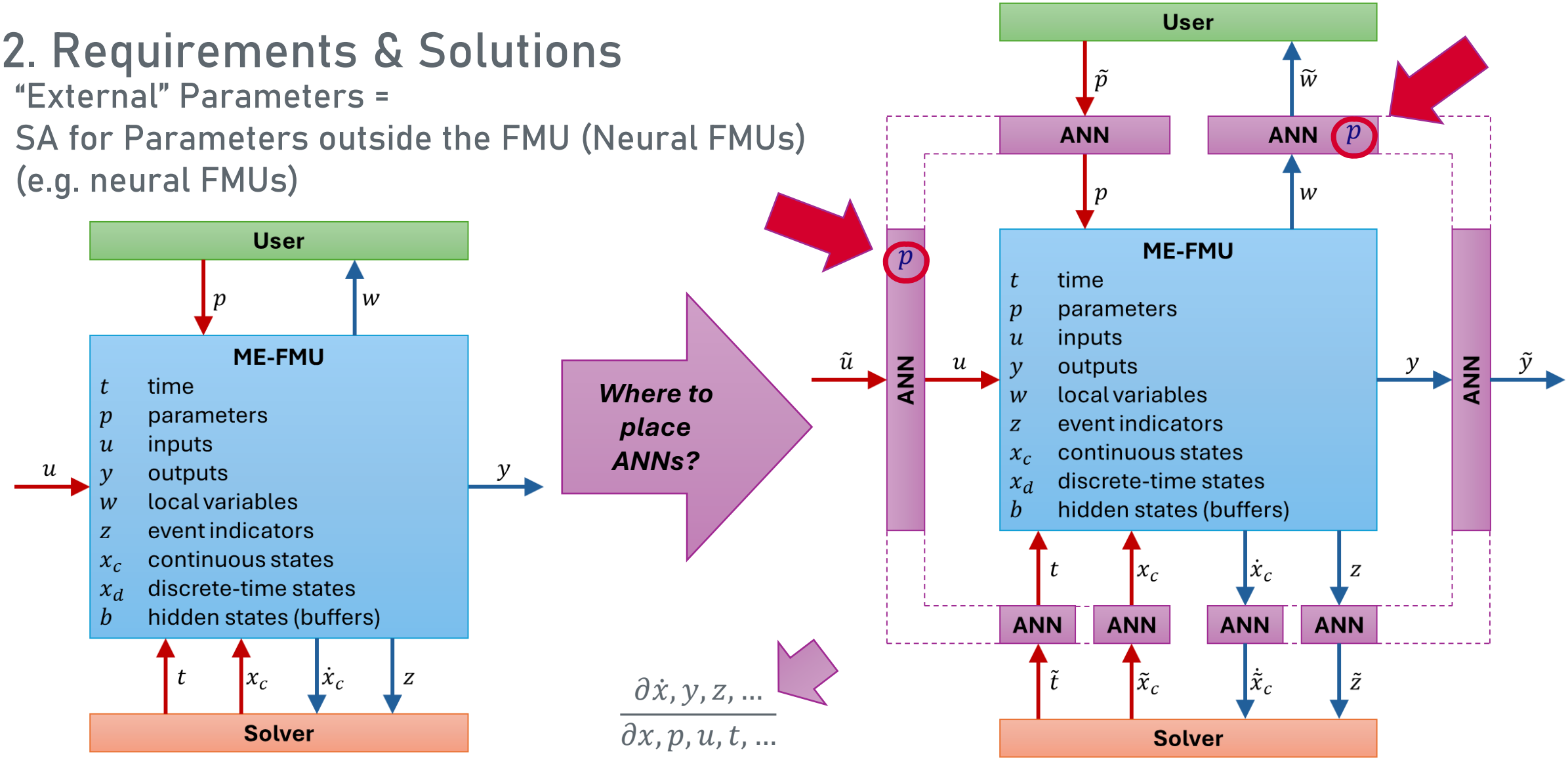
handle

7. State after event depends on state before → $\frac{\partial x^+}{\partial x^-}$
8. State after event depends on parameters → $\frac{\partial x^+}{\partial p}$

* Disclaimer: Only pure state events are investigated, no mixed-state-time events and no pure time events. Inputs are neglected. Optimization objective depends on the system state.

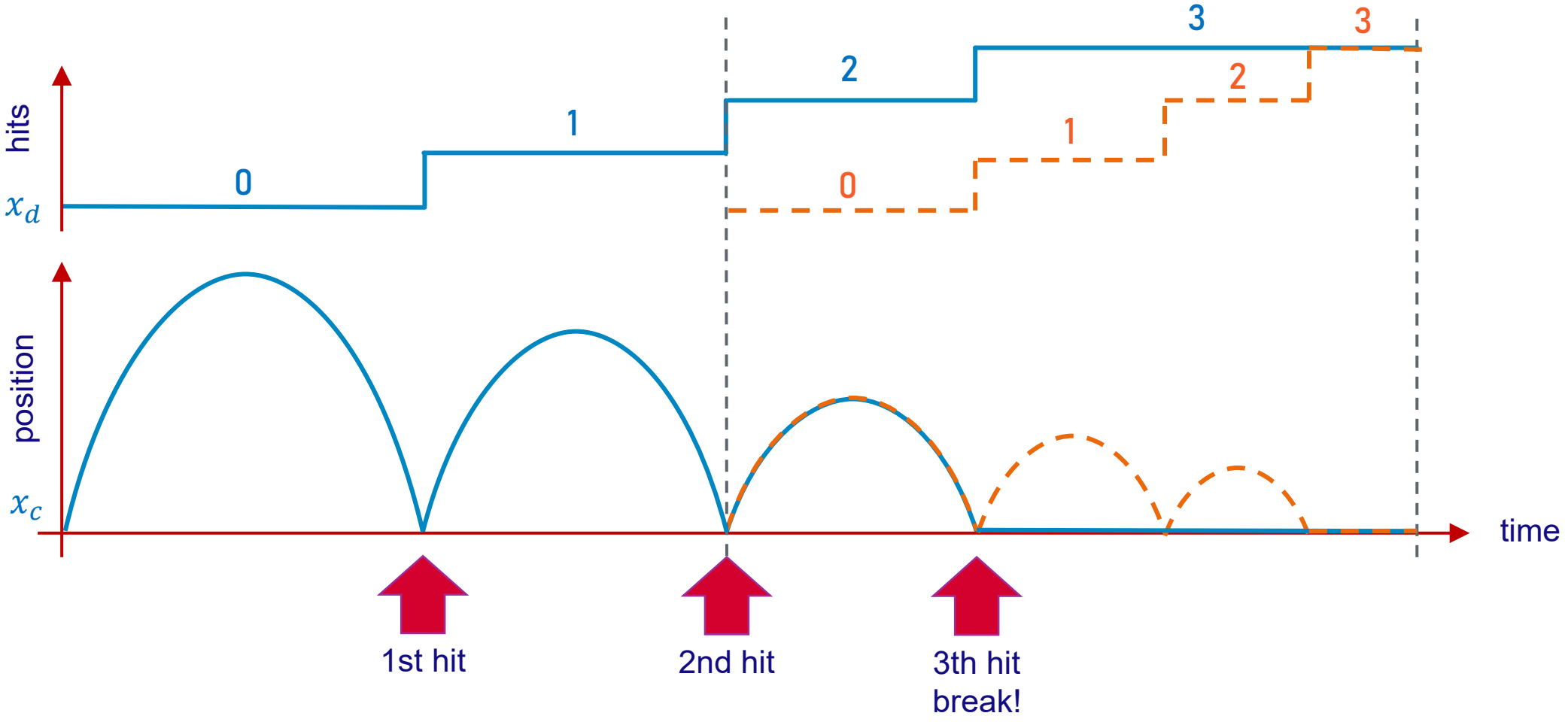
2. Requirements & Solutions

"External" Parameters =
SA for Parameters outside the FMU (Neural FMUs)
(e.g. neural FMUs)



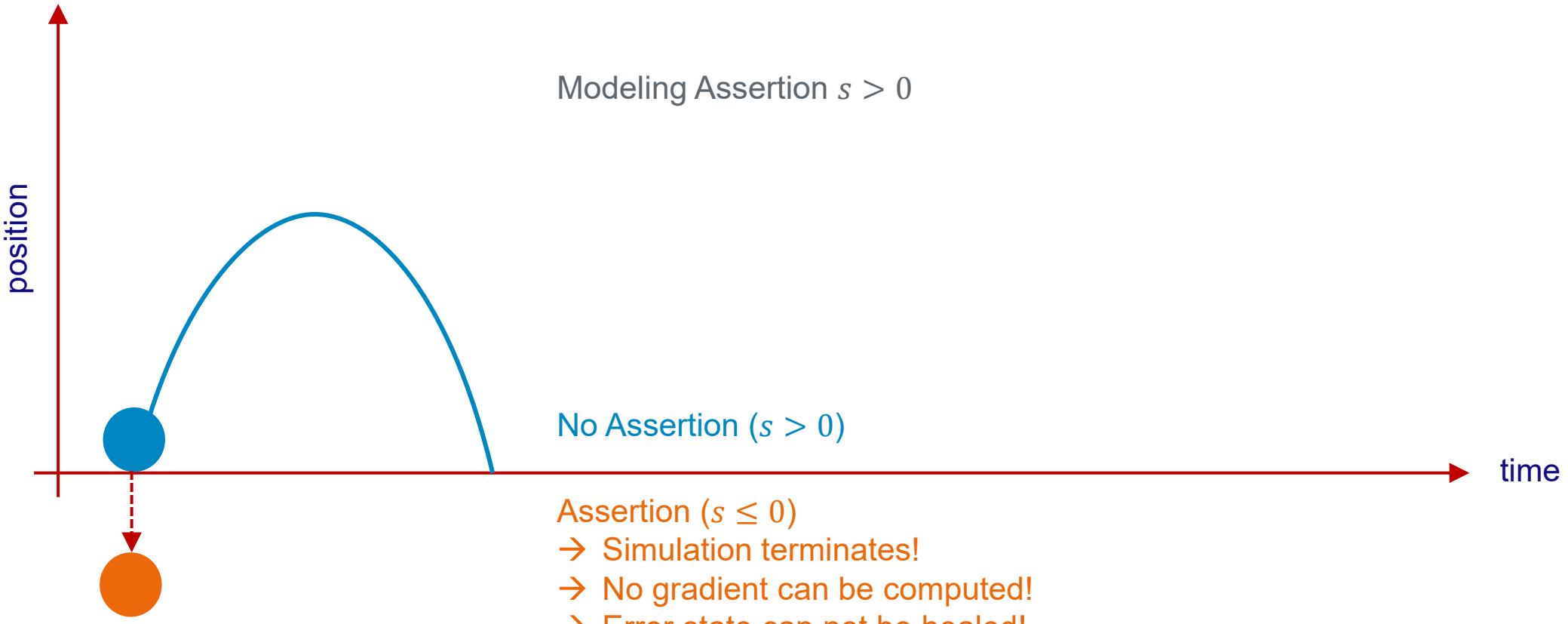
2. Requirements & Solutions

Expose the discrete states! Why?



2. Requirements & Solutions

Indicate modeling errors! Why?



2. Requirements & Solutions

Summary

Problem	Initial situation (FMI3)	Measure (Model Description)	Measure (Function Implementation)
Sensitivities w.r.t. to event indicators are required.	Event indicators are registered as model variables in FMI3.	/	Allow event indicators within `getDirectional/AdjointDerivative` to obtain JVPs/VJPs w.r.t. $\frac{\partial z}{\partial \{x,u,p,t,\dots\}}$.
The state after event x^+ (could) depend on the state before event x^-.	/	Add model variables for „previous“ states and …	… allow them within `getDirectional/AdjointDerivative` to obtain JVPs/VJPs w.r.t. $\frac{\partial x^+}{\partial x^-}$.
Sensitivities w.r.t. to explicit time are needed.	The independent variable („time“ in general) is already registered.	/	Allow indep. variable to be used within `getDirectional/AdjointDerivative` to obtain GVPs/VGPs w.r.t. $\frac{\partial \{z,y,\dot{x},\dots\}}{\partial t}$.
The discrete state is not exposed.	The concept of a discrete state exists, but it‘s completely hidden (no interface).	Expose discrete state within a new section `<DiscreteState>` as part of the `<ModelStructure>` and …	… allow the discrete state to be used within: `getX`, `setX` and `getDirectional/AdjointDerivative`.
Errors are not „measurable“, we just see them if it is too late (assertion).	/	Expose error indicators within a new section `<ErrorIndicator>` (same style as event indicators) as part of the `<ModelStructure>` and …	… allow these new model variables to be used within `getFloat64` and `getDirectional/AdjointDerivative`.

Important: No need to extend the function interface → less implementation effort

3

CONCLUSION & FUTURE WORK

Conclusion and Outlook

Summary

- Proposal for LS-SA, that is ACTIVE work – feel free to join!
- Allows for holistic and efficient SA for FMUs including events, e.g.:
- Parameter optimization (“model calibration”)
- Input optimization (“optimal control”)
- External paramteres (“Hybrid Modeling”)
- Focus on low effort of implementation:
- Parsing additional model information (extension for model description)
- Allowing new variables within existing function calls
- Explicitly no extension of the function interface needed

Current & Future Work

- Implementation of the LS-SA in a fork from Modelica Reference FMUs (export) and *FMI.jl* (import) to have a working pipeline to benchmark and show results
- Implementation of the LS-SA during OpenSCALING by some tool vendors

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Research funded by:

Open SCALING

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Thank you for your attention.

Questions? Feedback? Comments?

Yes, please!