MATLAB EXPO

November 13–14, 2024 | Online

Modeling Dynamic Systems with MATLAB and Simulink

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MathWorks

Models are crucial in any engineering project

Do you want to:

Design complex systems?

Simulate and test your system early and often?

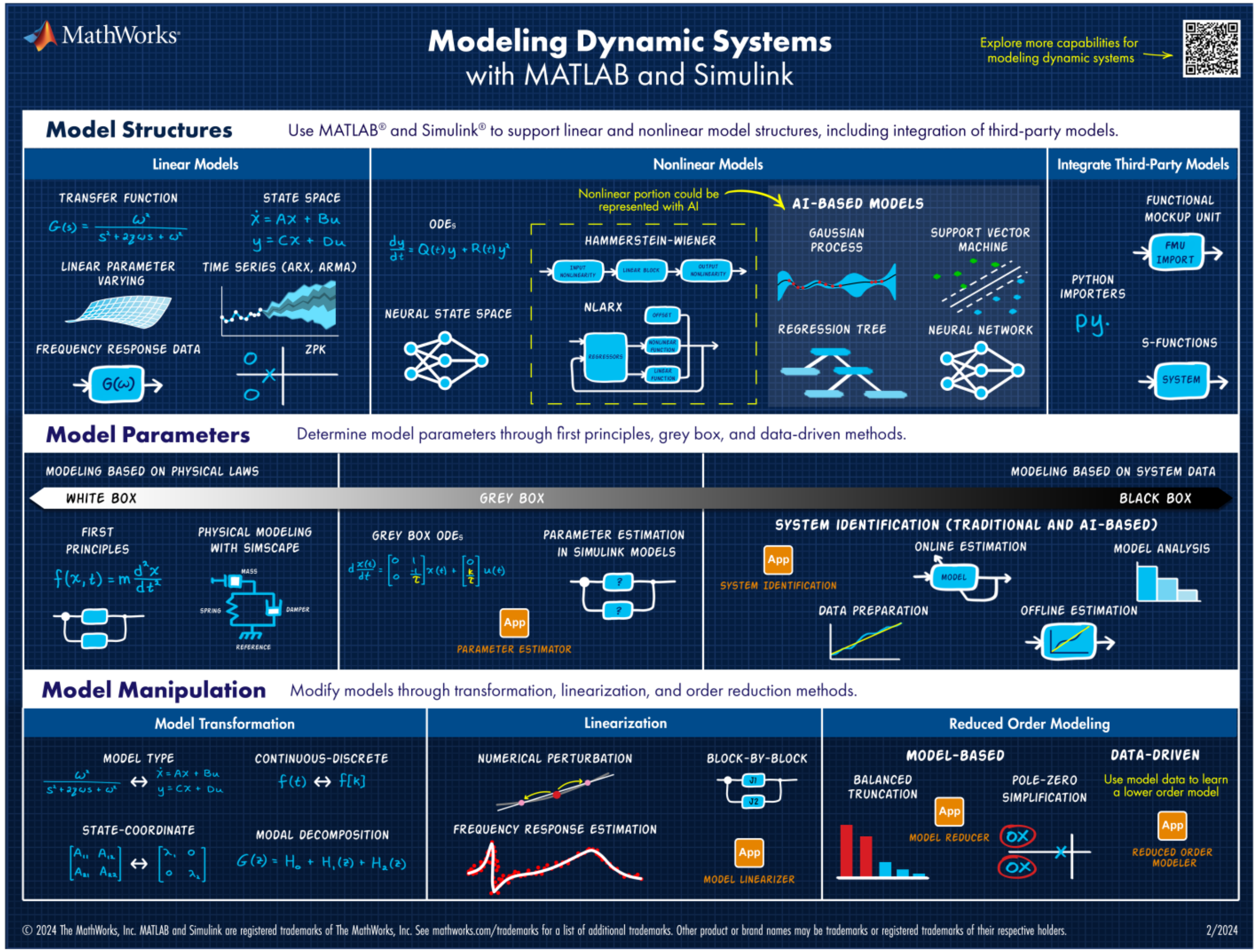
Analyze and validate your design?

Optimize system performance?

You need a model

And tools and methods for creating those models

There are many different capabilities that can help you model dynamic systems



[Modeling Dynamic Systems - MATLAB & Simulink (mathworks.com)](https://www.mathworks.com)

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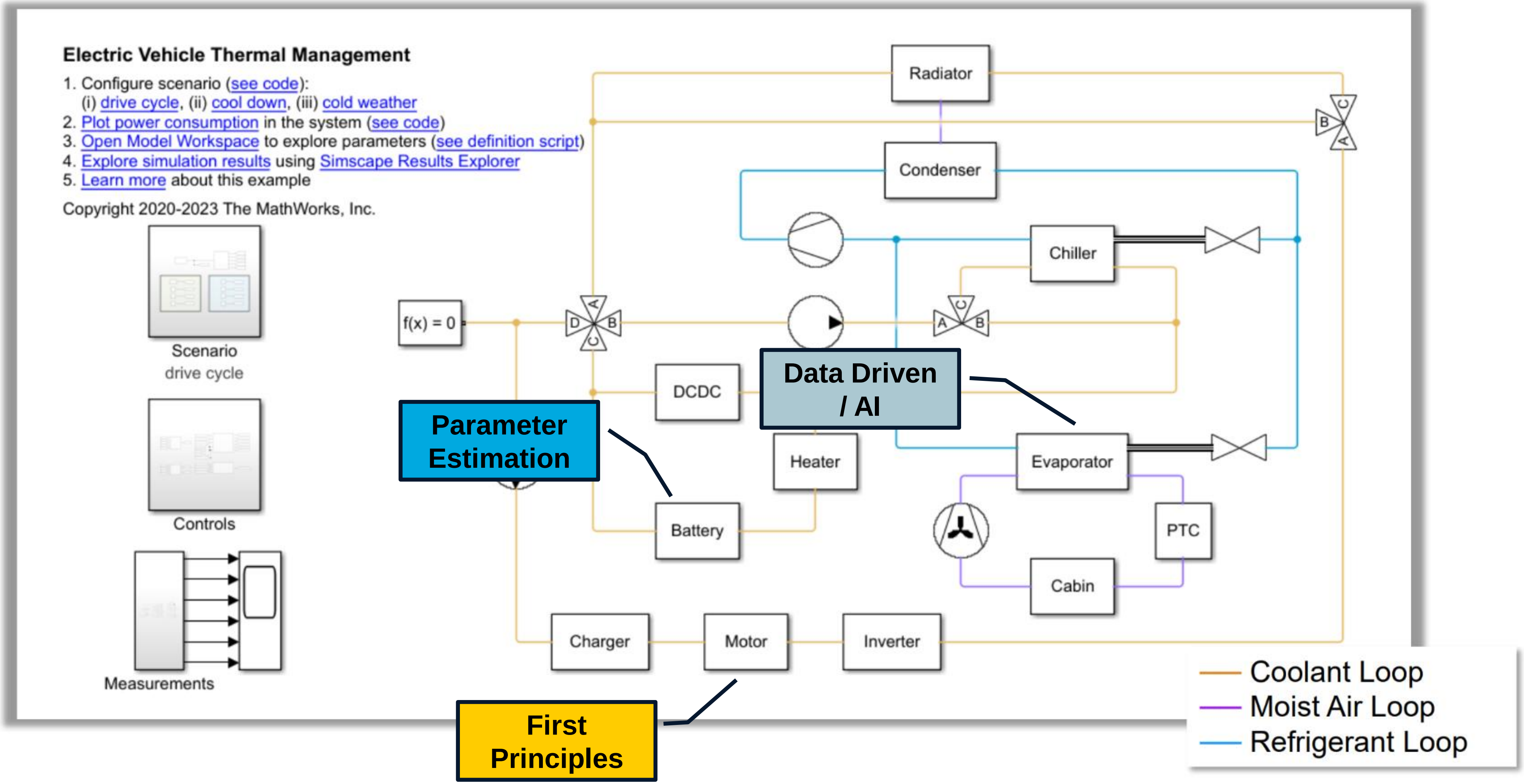
Components could be modeled with **different methods**



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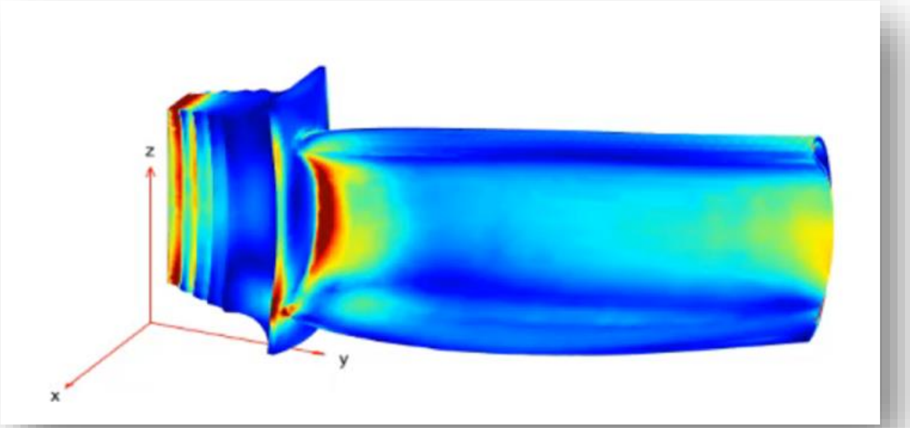
Models can **change form** depending on the use case.

High fidelity model

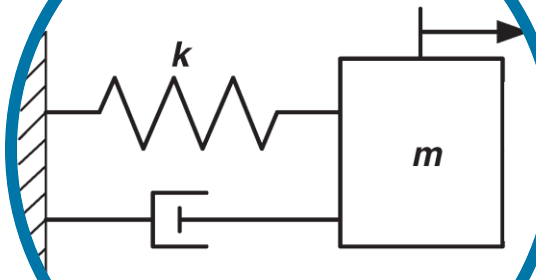


Reduced order modeling

Real-time simulation with HIL testing

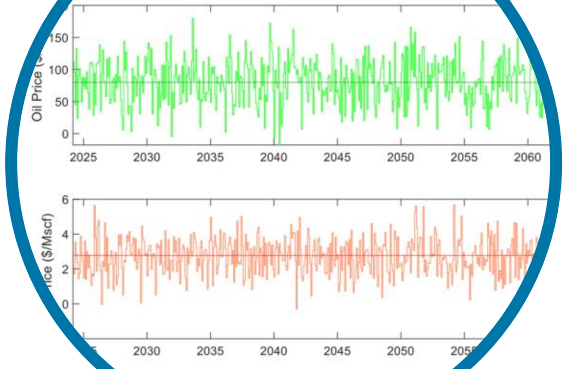
Where do you get the information to create a model?

Physics



First principles modeling

Data

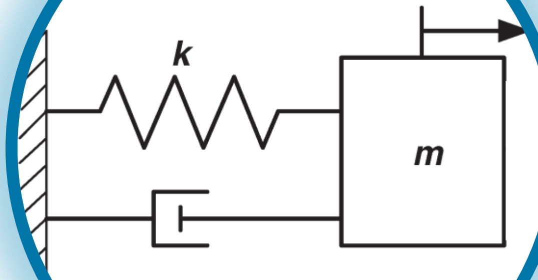


Data-driven modeling

WHITE BOX **BLACK BOX**

Where do you get the information to create a model?

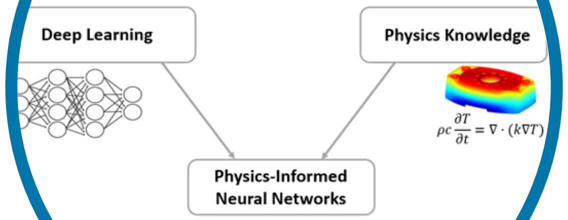
Physics



First principles modeling

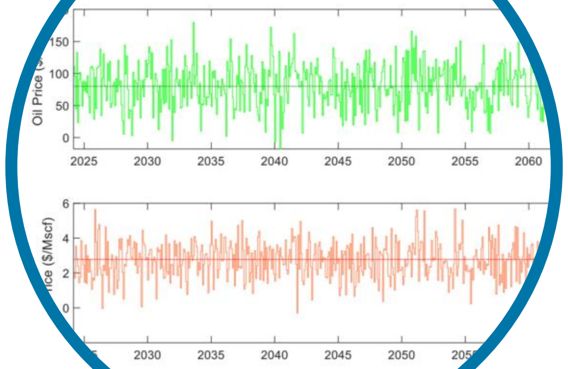
$$m\ddot{x} + b\dot{x} + kx = 0$$

Parameter estimation



Physics-Informed ML

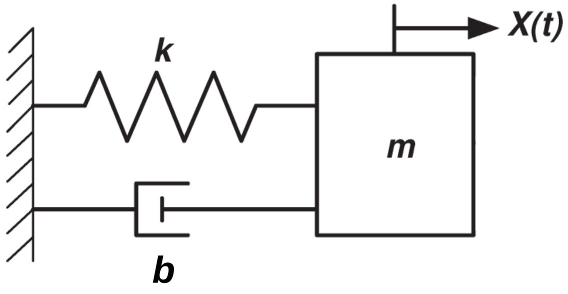
Data



Data-driven modeling

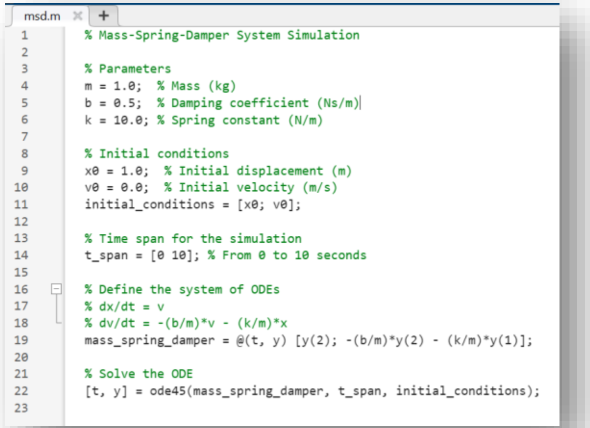
WHITE BOX **BLACK BOX**

With first principles modeling you build models that are based on physical laws



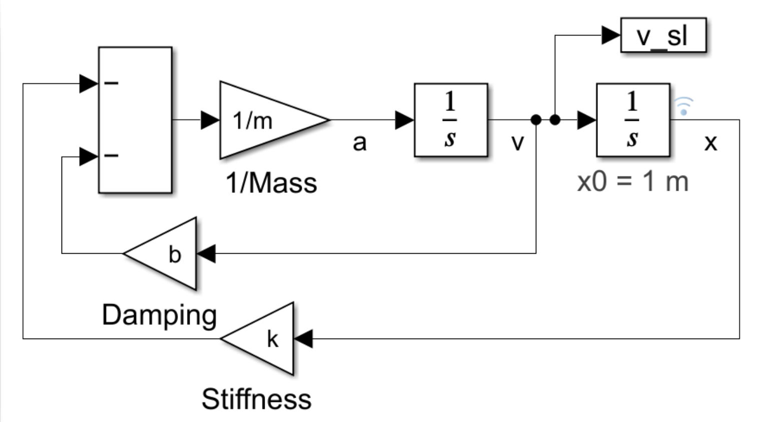
$$m\ddot{x} + b\dot{x} + kx = 0$$

Text-based code

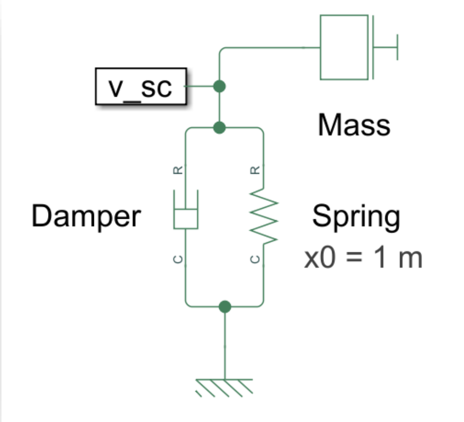



```matlab
% Mass-Spring-Damper System Simulation

% Parameters
m = 1.0;  % Mass (kg)
b = 0.5;  % Damping coefficient (Ns/m)
k = 10.0; % Spring constant (N/m)

% Initial conditions
x0 = 1.0;  % Initial displacement (m)
v0 = 0.0;  % Initial velocity (m/s)
initial_conditions = [x0; v0];

% Time span for the simulation
t_span = [0 10]; % From 0 to 10 seconds

% Define the system of ODEs
% dx/dt = v
% dv/dt = -(b/m)*v - (k/m)*x
mass_spring_damper = @(t, y) [y(2); -(b/m)*y(2) - (k/m)*y(1)];

% Solve the ODE
[t, y] = ode45(mass_spring_damper, t_span, initial_conditions);
```

Executable block diagrams

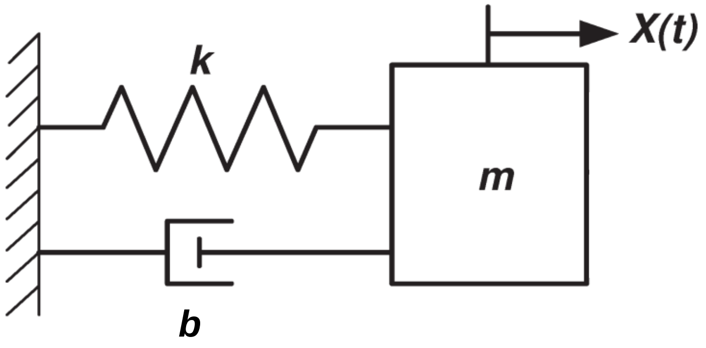


Physical modeling



There are benefits to first principles modeling

Insight and interpretability

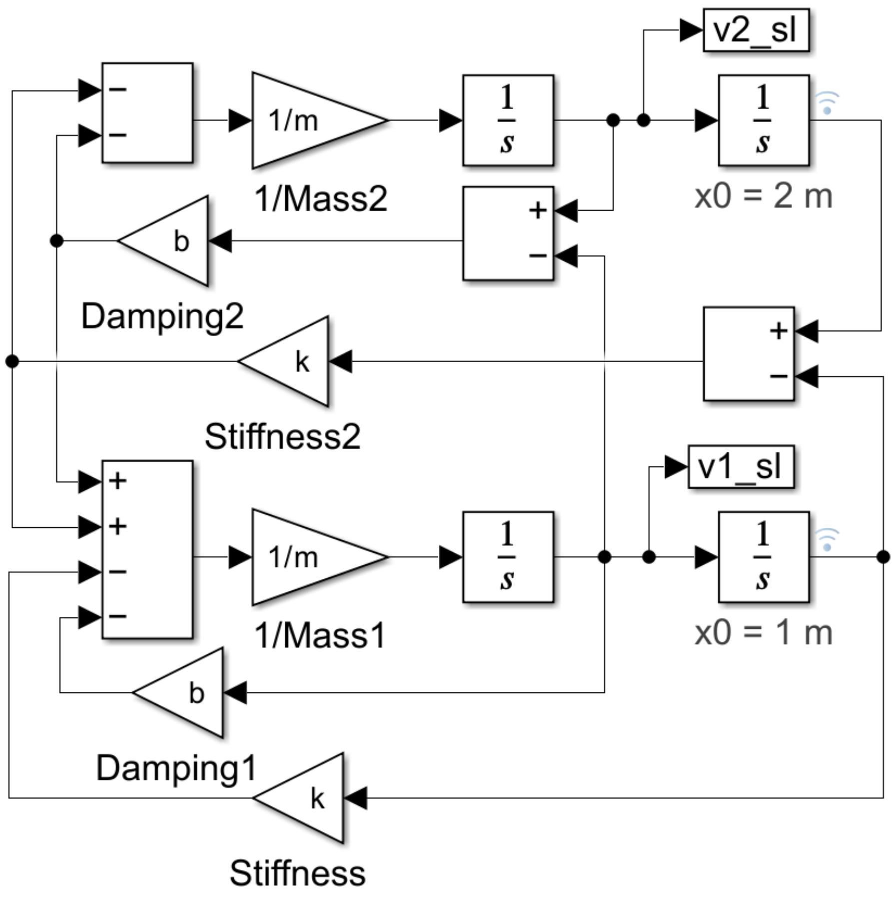


First principles model

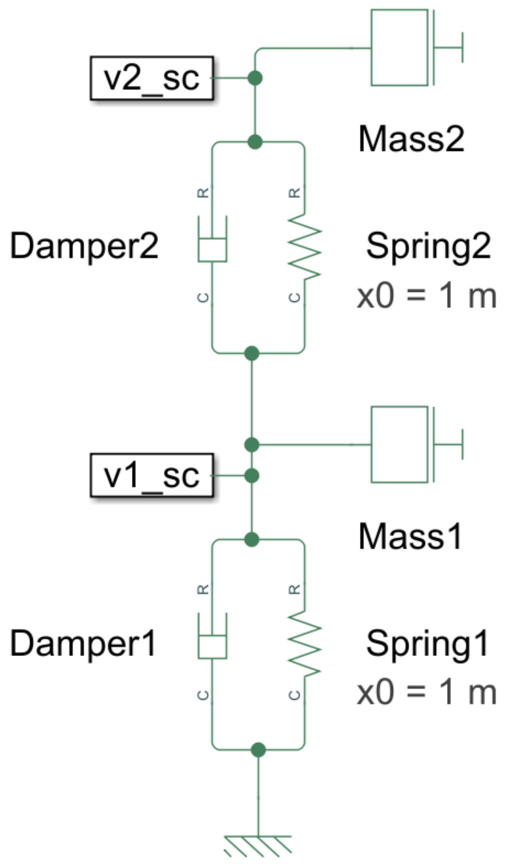
$$\underbrace{m\ddot{x} + b\dot{x} + kx = 0}_{\text{This is understandable}}$$

Physical modeling of first principles can be even more interpretable than equations

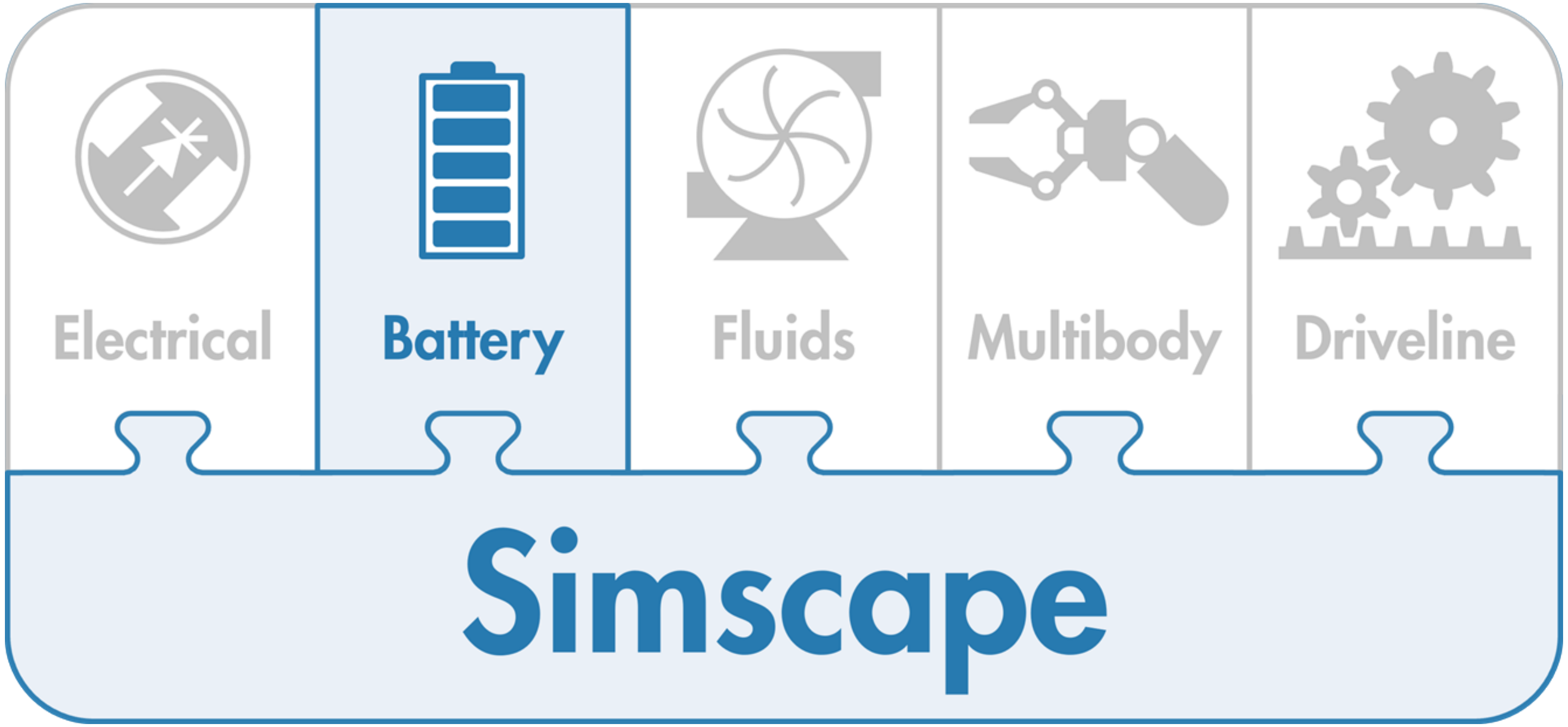
Simulink Model



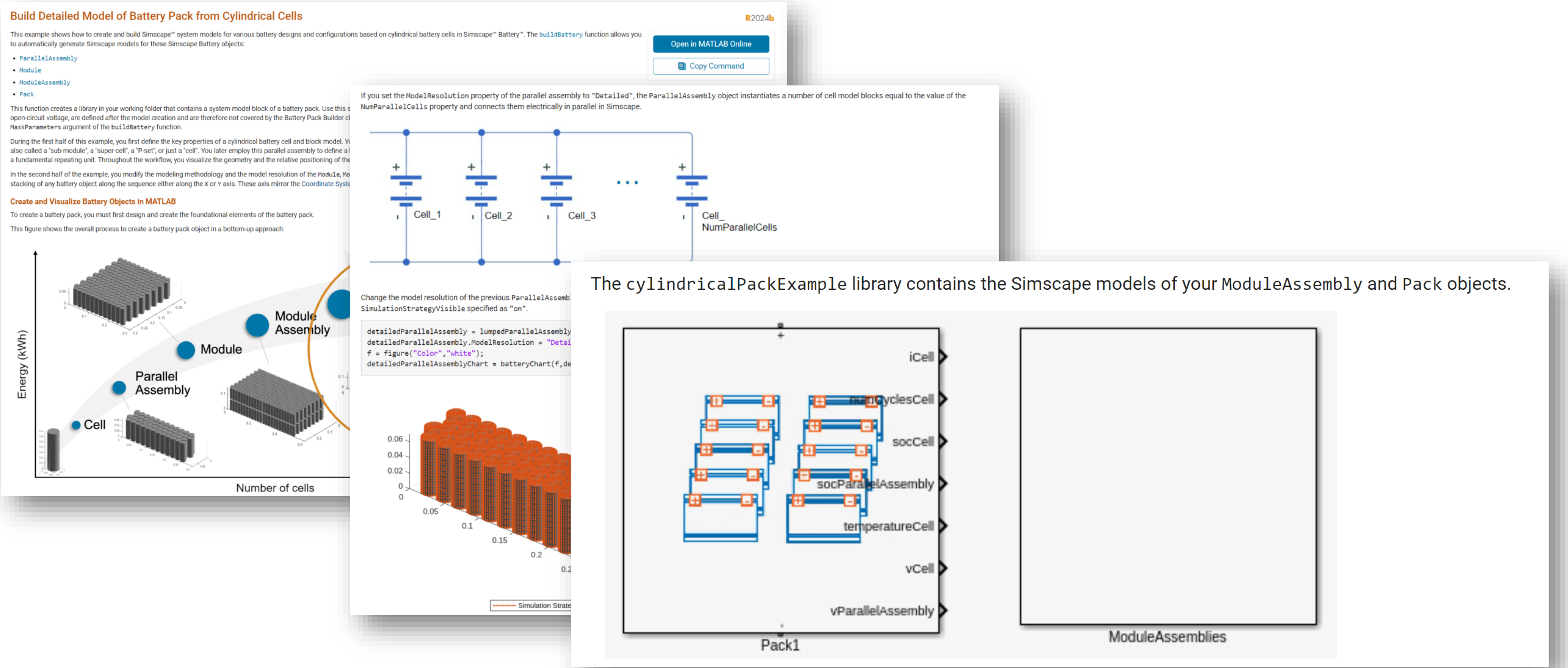
Simscape Model



Spring-mass-dampers are good examples to learn but what about more complex dynamics?



Build a detailed model of a battery pack easily with physical modeling



[Build Detailed Model of Battery Pack from Cylindrical Cells - MATLAB & Simulink (mathworks.com)]

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First principles modeling is used by our customers for a variety of applications

Link to User Story

Virtual Design and Testing of an Autonomous Rescue Drone Speeds Up Product Development

Simscape™ was used for detailed models of the subsystems, including the electric powertrain with battery, intermediate circuit, inverter, and engine.

Image credit: SEGULA Technologies

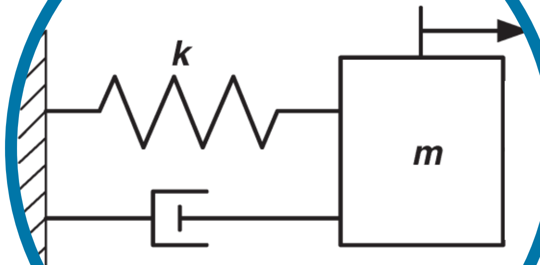
Link to User Story

This Clean Power Source Is Helping Fuel the Future of Transportation

> Starting with a Simscape model shaves four to six weeks off of the initial development time.
>
> *-Dirk Rensink*
> *Technical lead for fuel cell simulation, SEGULA Technologies*

Where do you get the information to create a model?

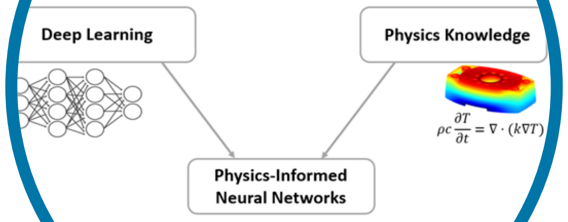
Physics



First principles modeling

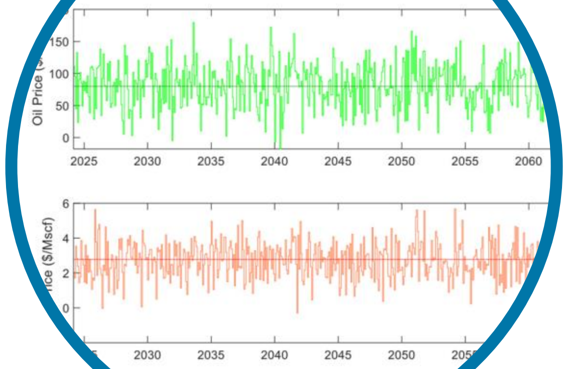
$$m\ddot{x} + b\dot{x} + kx = 0$$

Parameter estimation



Physics-Informed ML

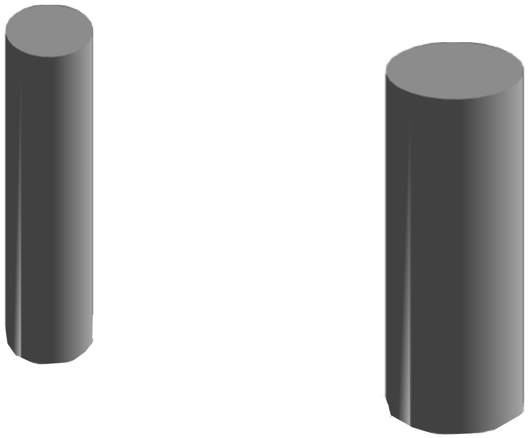
Data



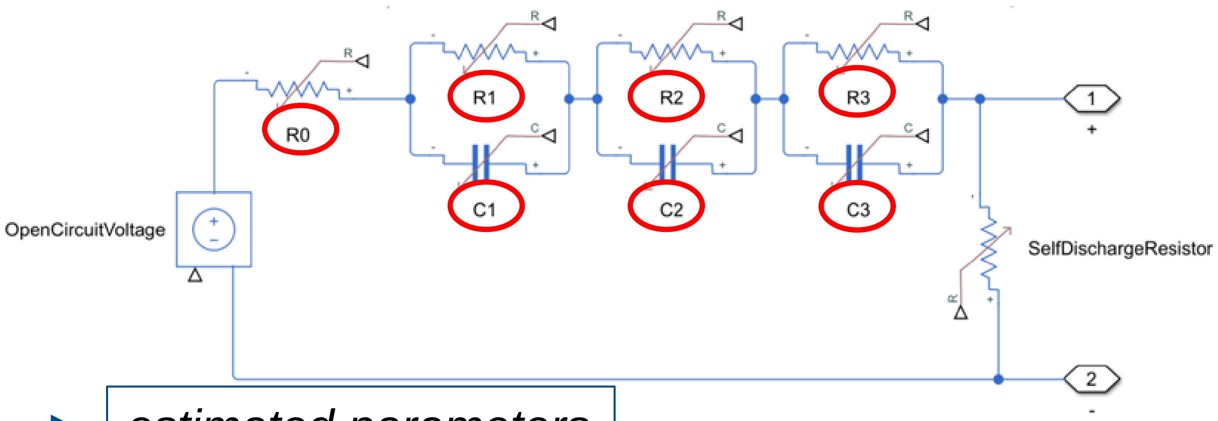
Data-driven modeling

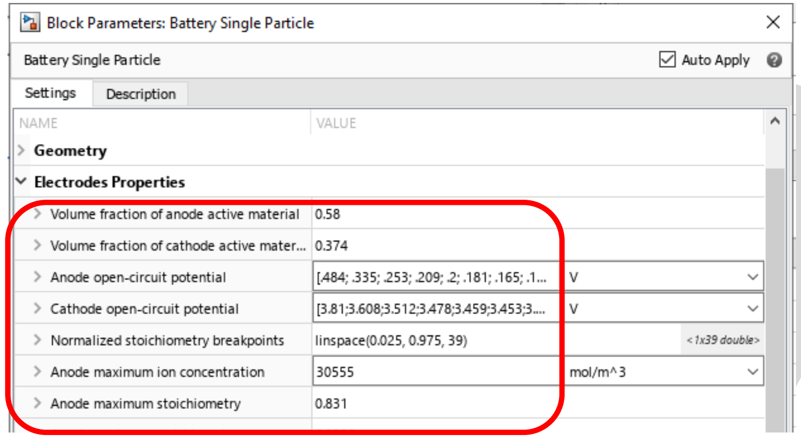
WHITE BOX **BLACK BOX**

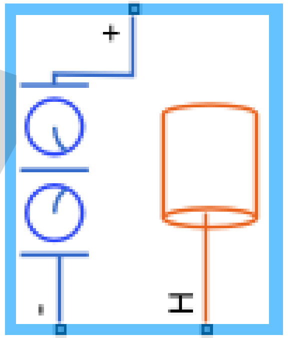
With parameter estimation you identify physically meaningful parameters using system equations and measured data



experimental data → **Parameter Estimation** → *estimated parameters*







Battery Single Particle Block

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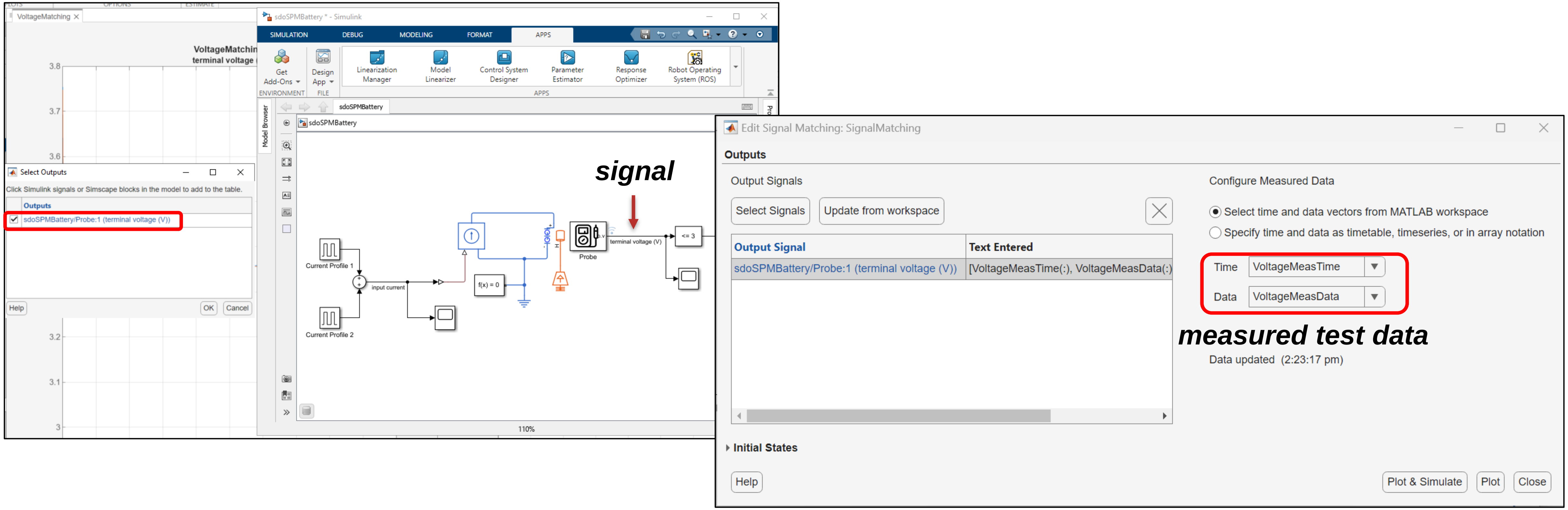
Parameter estimation with Simulink Design Optimization

Specify Experiment

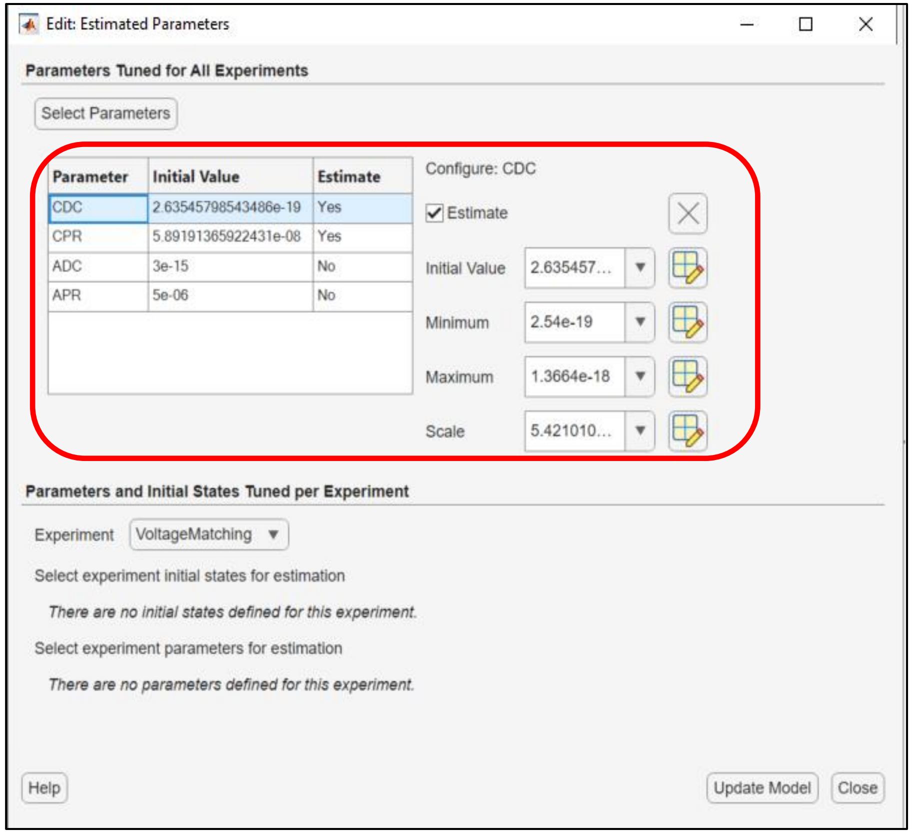


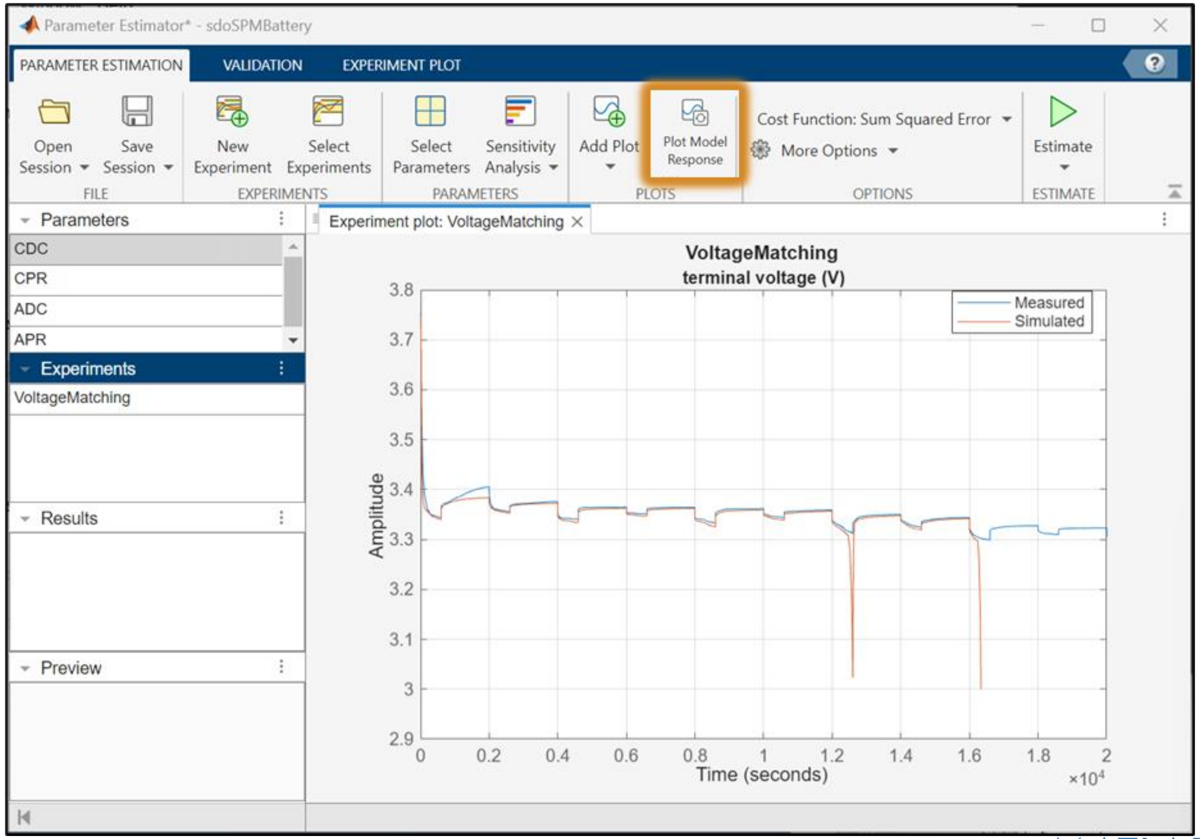
MATLAB EXPO

Parameter estimation with Simulink Design Optimization

Specify Experiment

Select Parameters

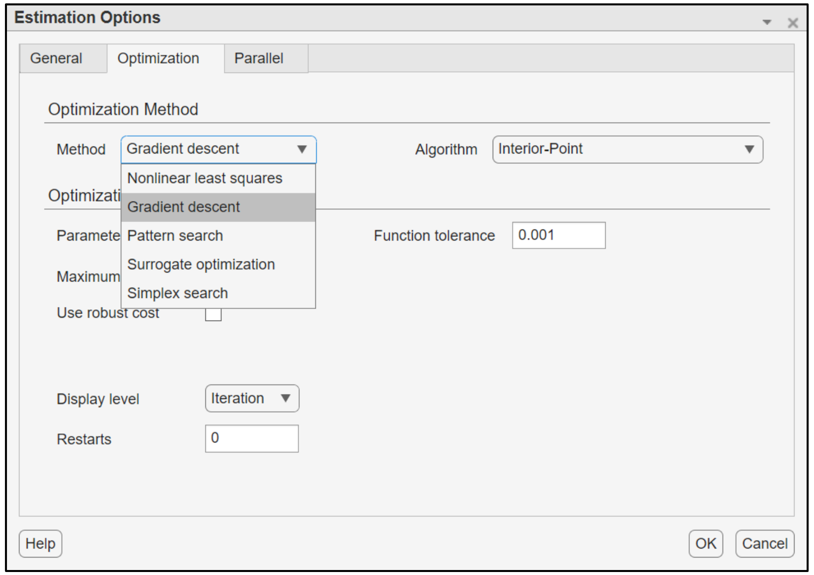


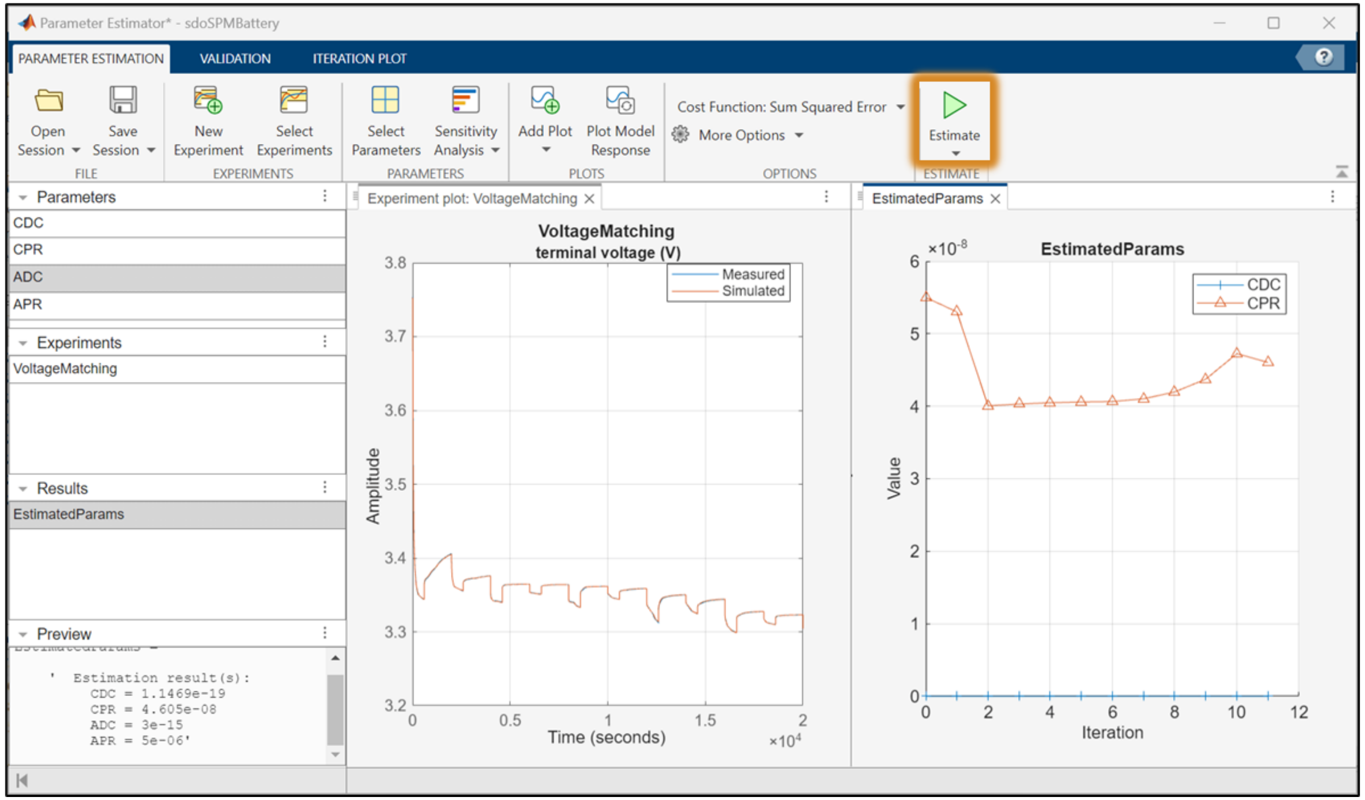


MATLAB EXPO

Parameter estimation with Simulink Design Optimization

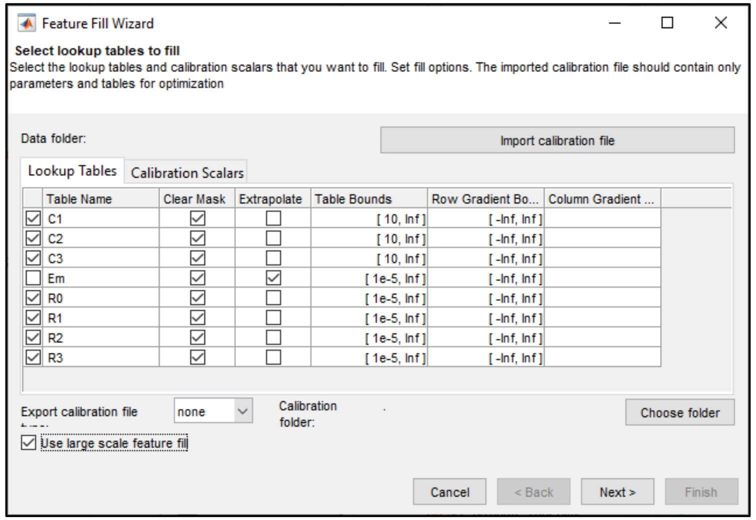
Specify Experiment → Select Parameters → Estimate Parameters

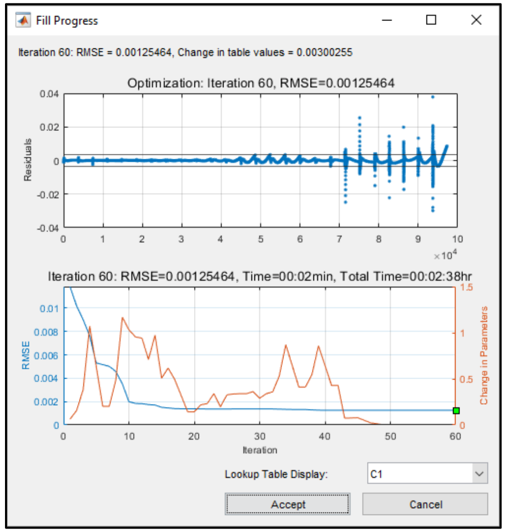




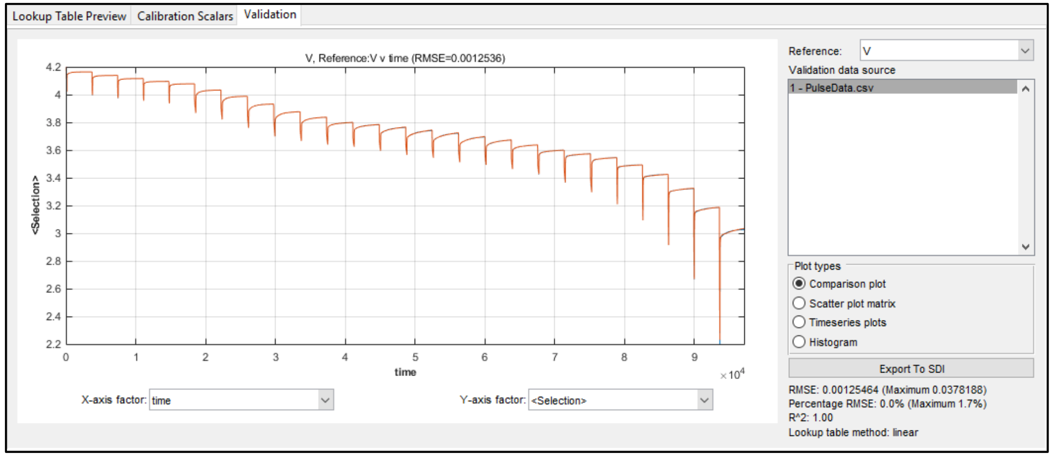
[Parameter estimation of a single-particle battery model with electrolyte dynamics (SPMe) - MATLAB & Simulink (mathworks.com)]

Parameter estimation with Model-Based Calibration Toolbox





Estimate battery model lookup tables from experimental data



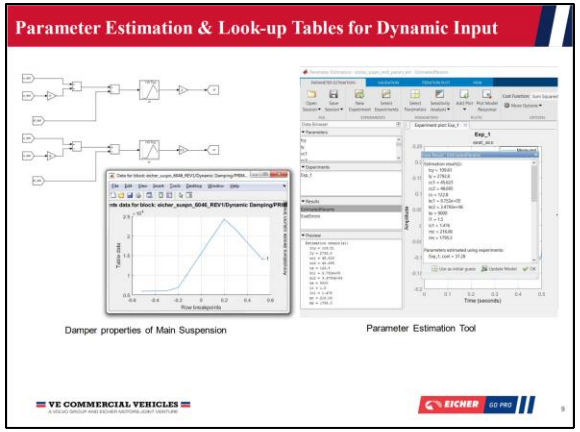
 [Characterize Battery Block Parameters in CAGE - MATLAB & Simulink (mathworks.com)]

Parameter estimation is used by our customers for a variety of applications

Link to User Story

Krones Develops Package-Handling Robot Digital Twin

Simulink Design Optimization™ was used to enhance model accuracy by fitting parameters to experimental data from the tripod robot tests.

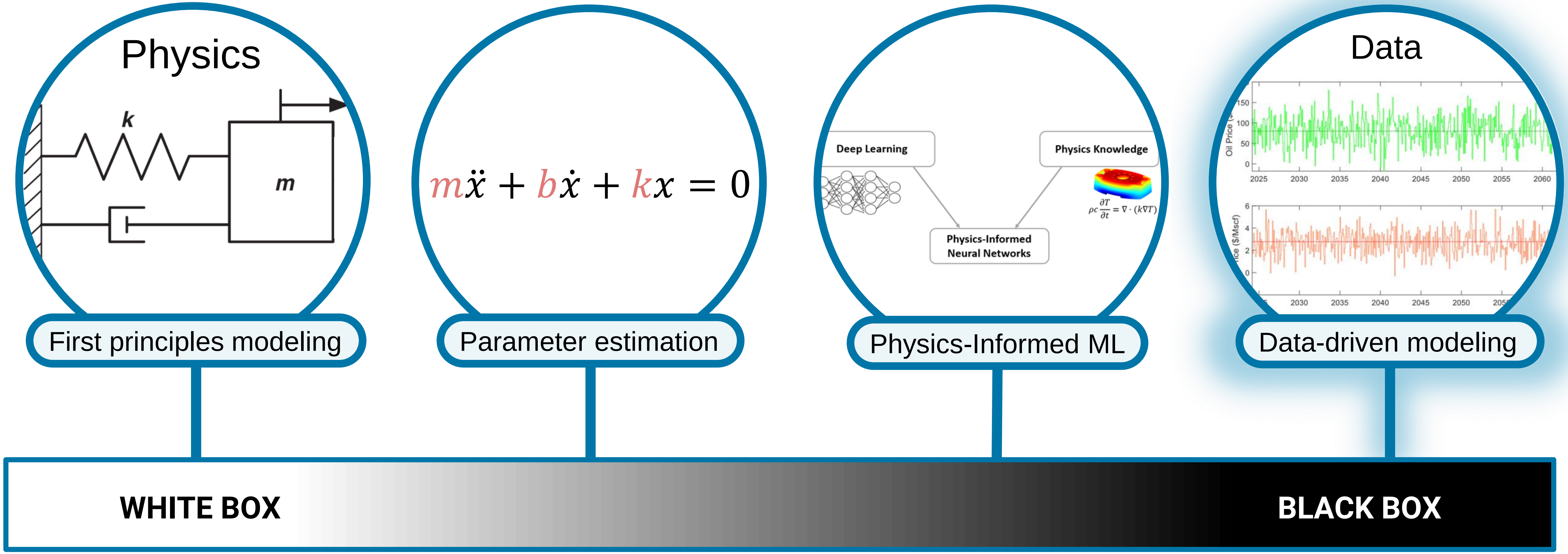


Link to User Story

VE Commercial Vehicles Establishes Ride Comfort Characteristics of Tractor-Semitrailers

> “In a tractor-trailer, we get many components from suppliers and sometimes the parameter what we need may or may not occur during our testing. Simulink Design Optimization™ is a very handy tool when it comes to identify some of these unknown parameters.”
>
> *-Sarnab Debnath*
> *VE Commercial vehicles Ltd*

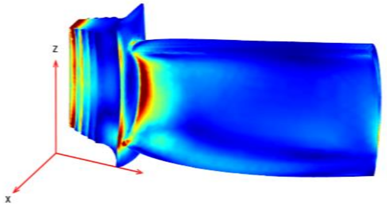
Where do you get the information to create a model?



With data-driven modeling you build models that are based on measured or generated data

Gather Experimental Data

Input



data from hardware (measured data)

data from full-order models (generated data)

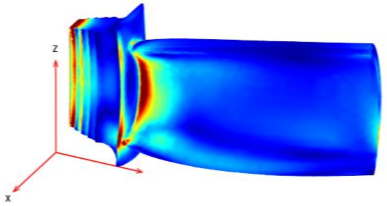
Output

With data-driven modeling you build models that are based on measured or generated data

Gather Experimental Data

Estimate Model from Data

Input

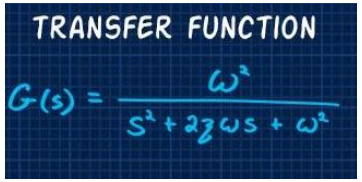


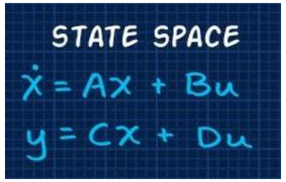
data from hardware (measured data)

data from full-order models (generated data)

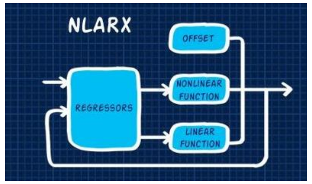
Output

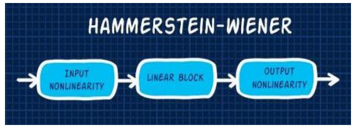
Linear Models

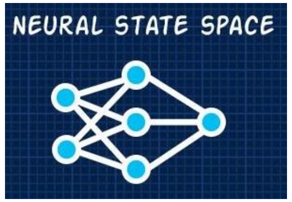


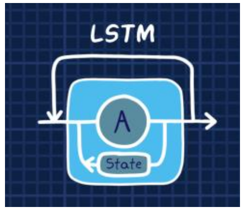


Nonlinear Models









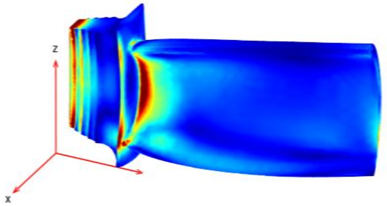
With data-driven modeling you build models that are based on measured or generated data

Gather Experimental Data

Estimate Model from Data

Validate Model with Independent Data

Input

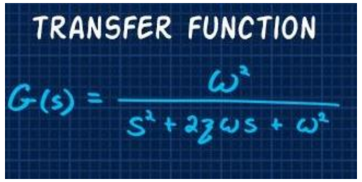


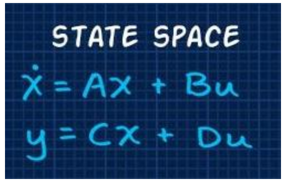
data from hardware (measured data)

data from full-order models (generated data)

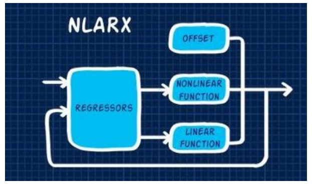
Output

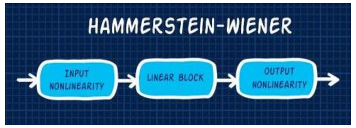
Linear Models

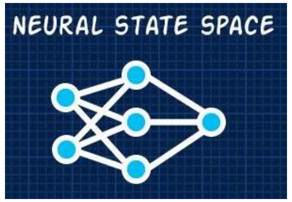


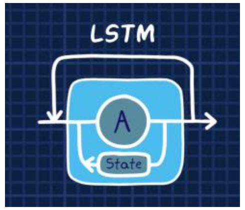


Nonlinear Models

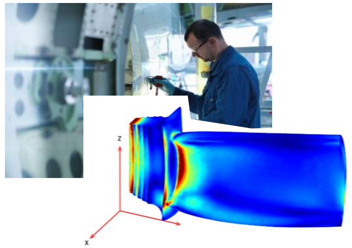


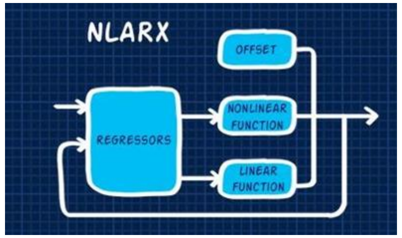






Input





original model

estimated model

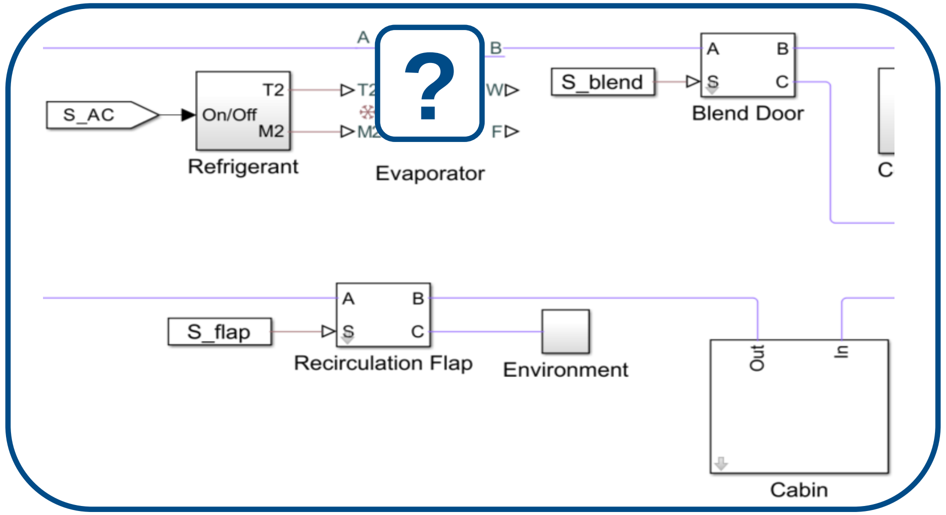
compare

Real Output

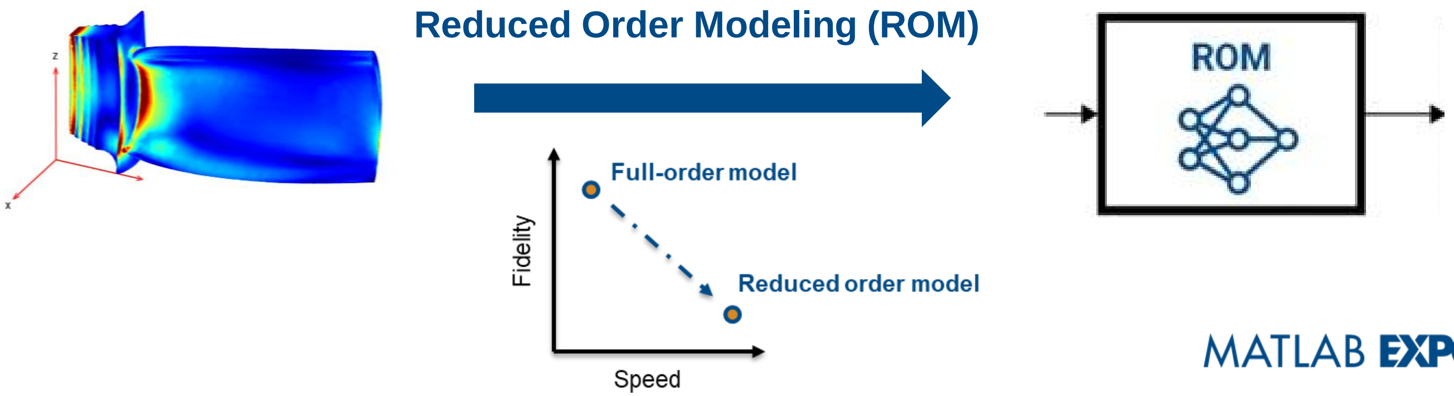
Estimated Output

There are benefits to data-driven modeling

Identify models when first-principles models are difficult to derive

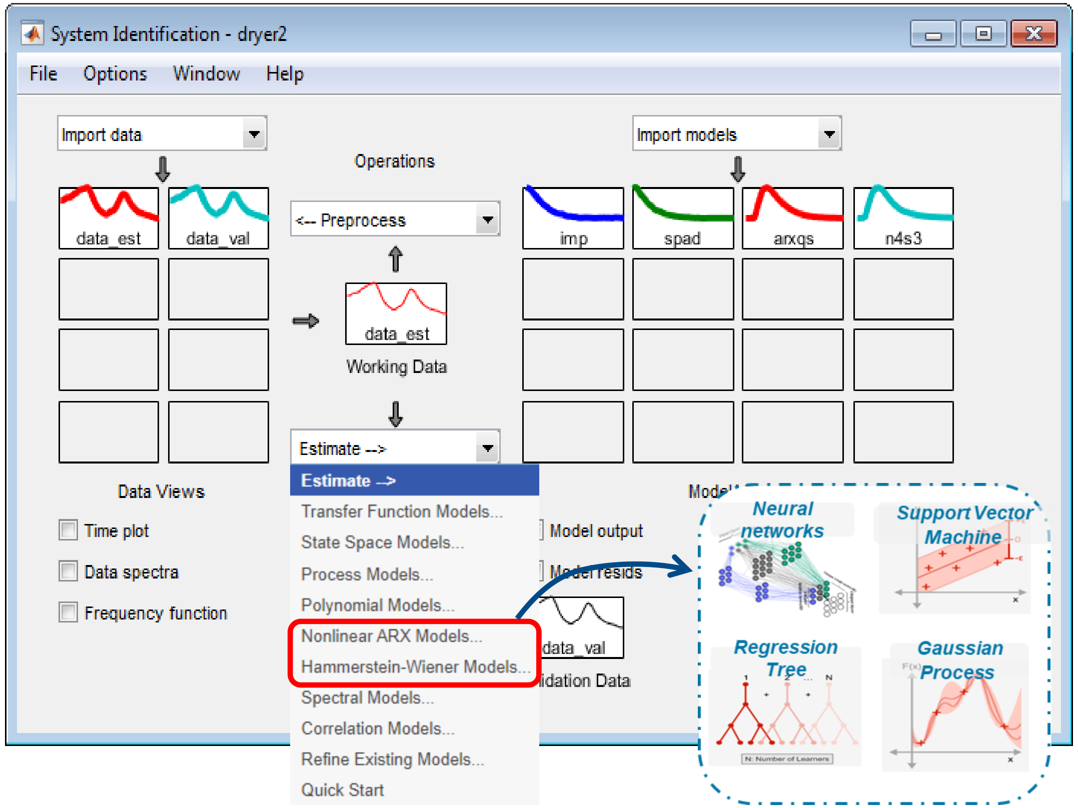


Reduce complexity by capturing only the dynamics of interest



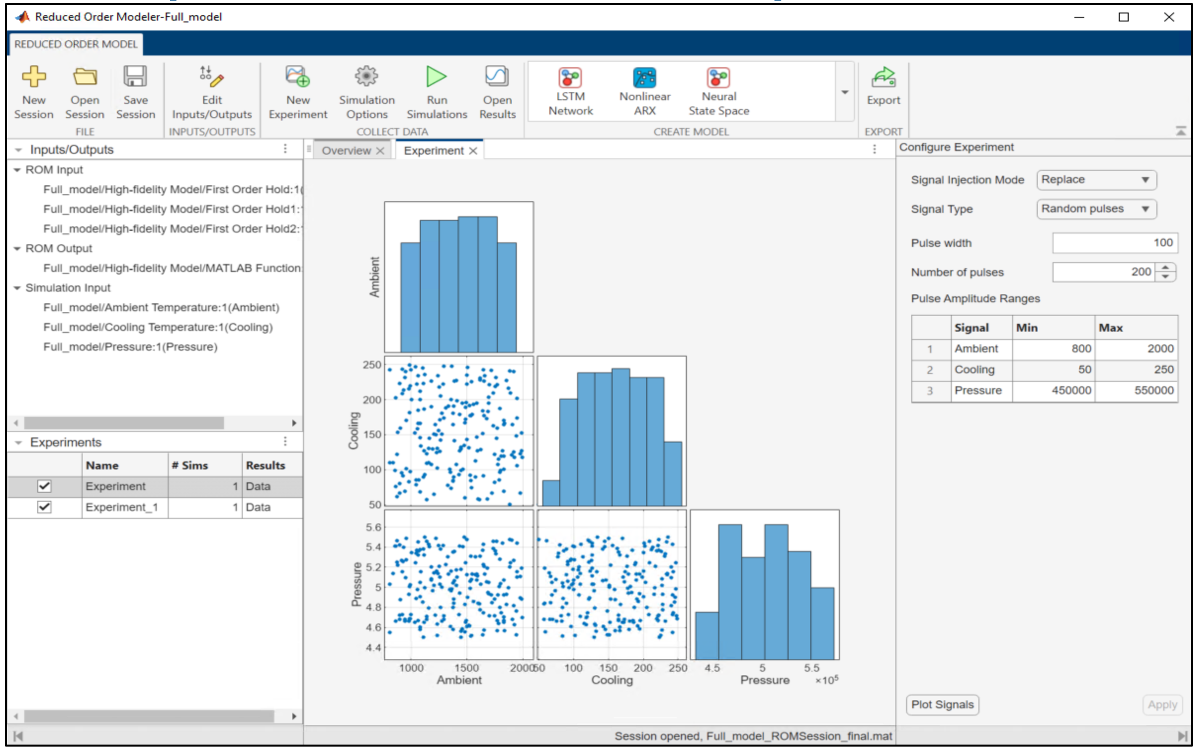
Data-Driven Modeling in MATLAB and Simulink

System Identification App
(data from hardware)



[System Identification Toolbox Examples - MATLAB & Simulink (mathworks.com)]

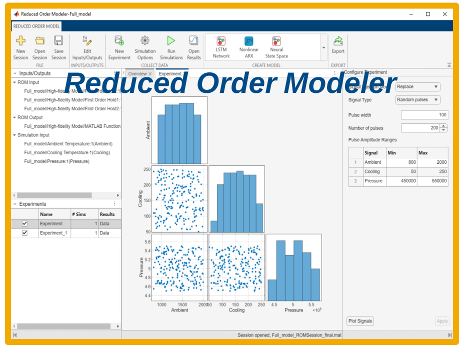
Reduced Order Modeler App
(data from full-order model)



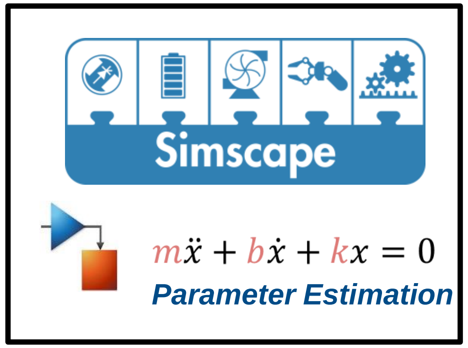
[Reduced Oder Model of a Jet EngineTurbine Blade - MATLAB & Simulink (mathworks.com)]

AI-based Reduced Order Modeling is one of the many ROM Techniques that MathWorks offers

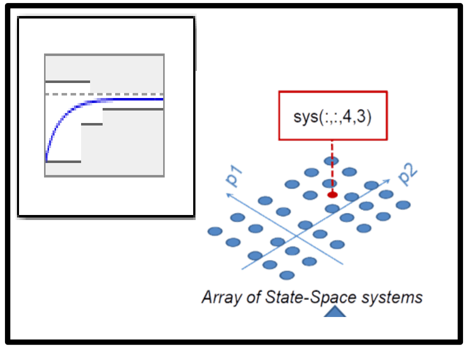
AI-Based ROM | **Non-AI-Based ROM**



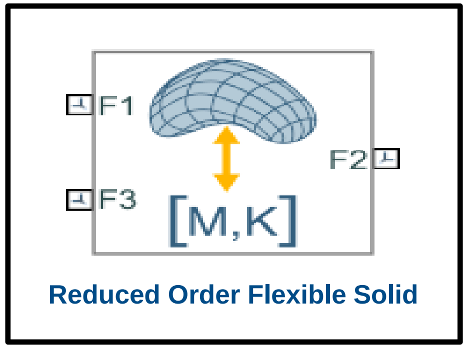
AI-Based Data-Driven



Physics-Based



Linearization

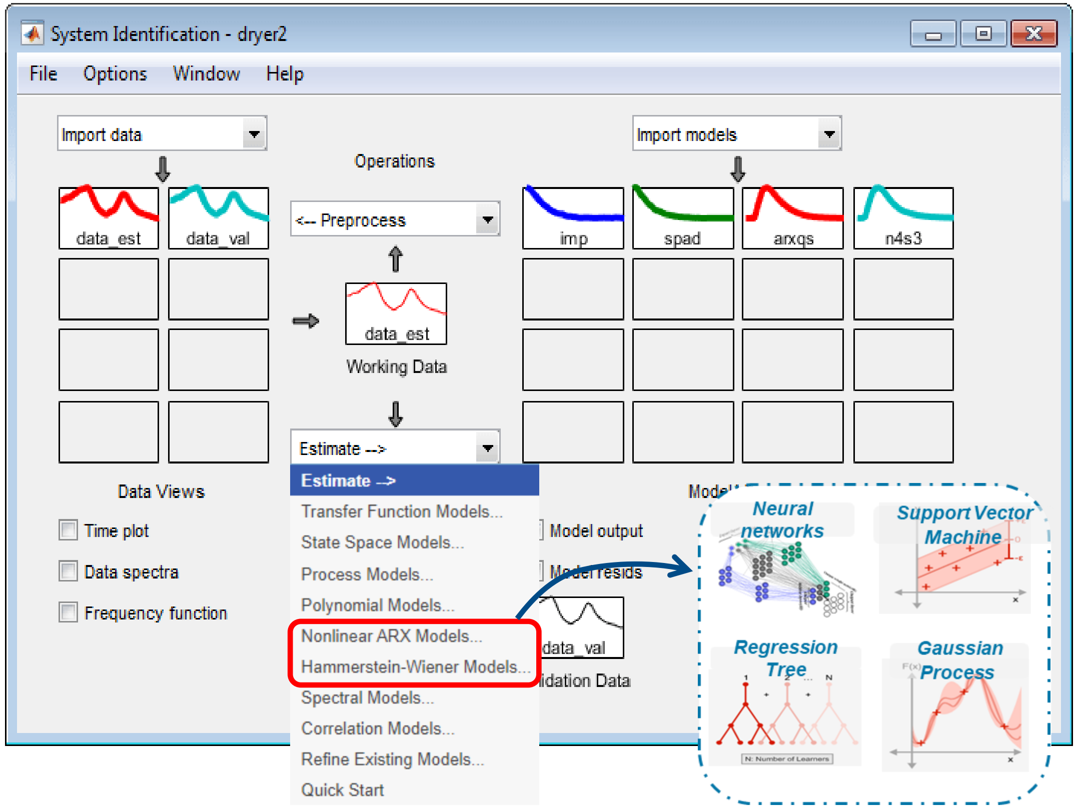


Model-Based

[Reduced Order Modeling - MATLAB & Simulink (mathworks.com)](mathworks.com)

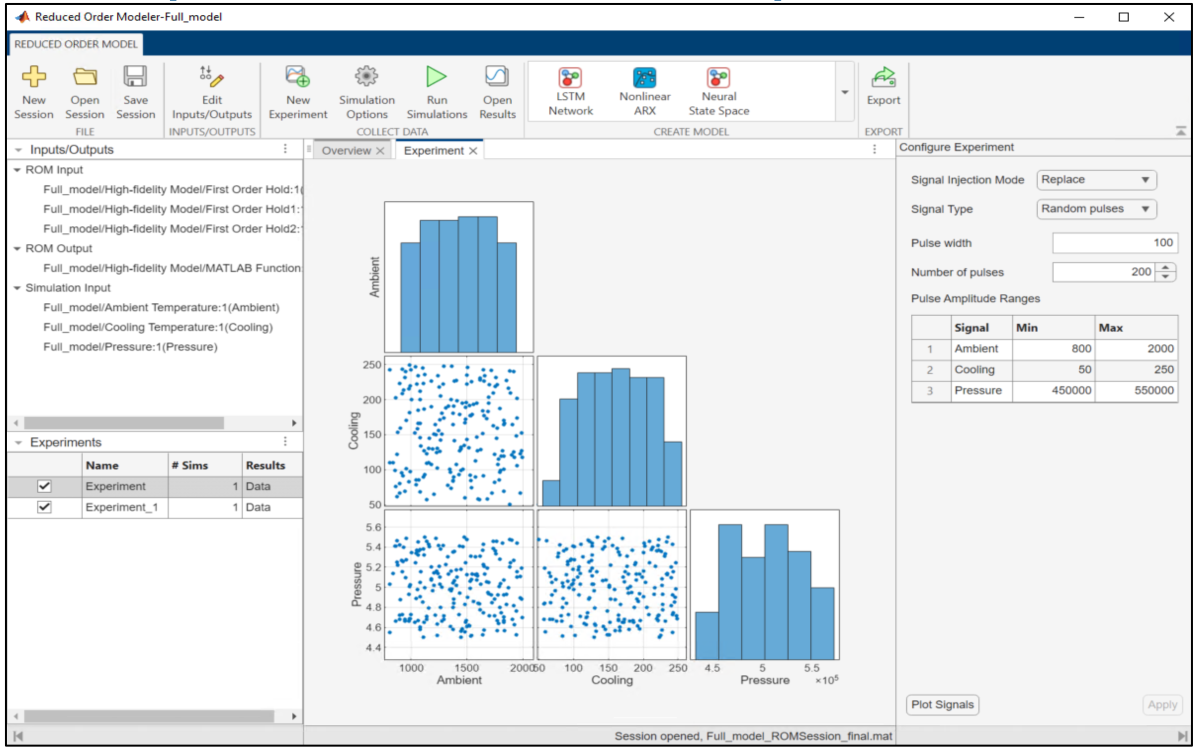
Data-Driven Modeling in MATLAB and Simulink

System Identification App (data from hardware)



[System Identification Toolbox Examples - MATLAB & Simulink (mathworks.com)]

Reduced Order Modeler App (data from full-order model)



[Reduced Oder Model of a Jet EngineTurbine Blade - MATLAB & Simulink (mathworks.com)]

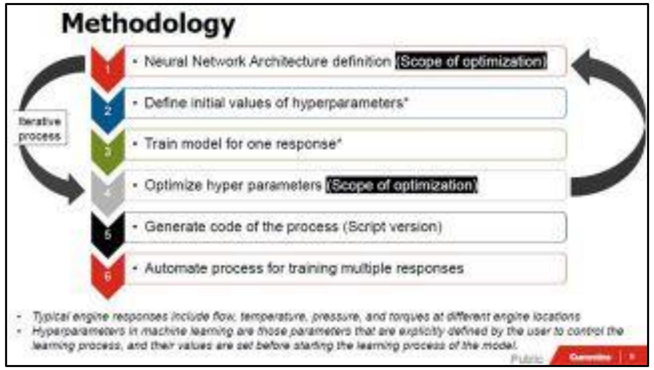
MATLAB EXPO

Data-Driven modeling is used by our customers for a variety of applications

[Link to User Story]

Ather Energy Develops Electric Two-Wheeled Scooter and Charging Stations Using Model-Based Design

System Identification Toolbox™ was used to create a model of battery cells, capturing their electrical and thermal characteristics using input-output data.

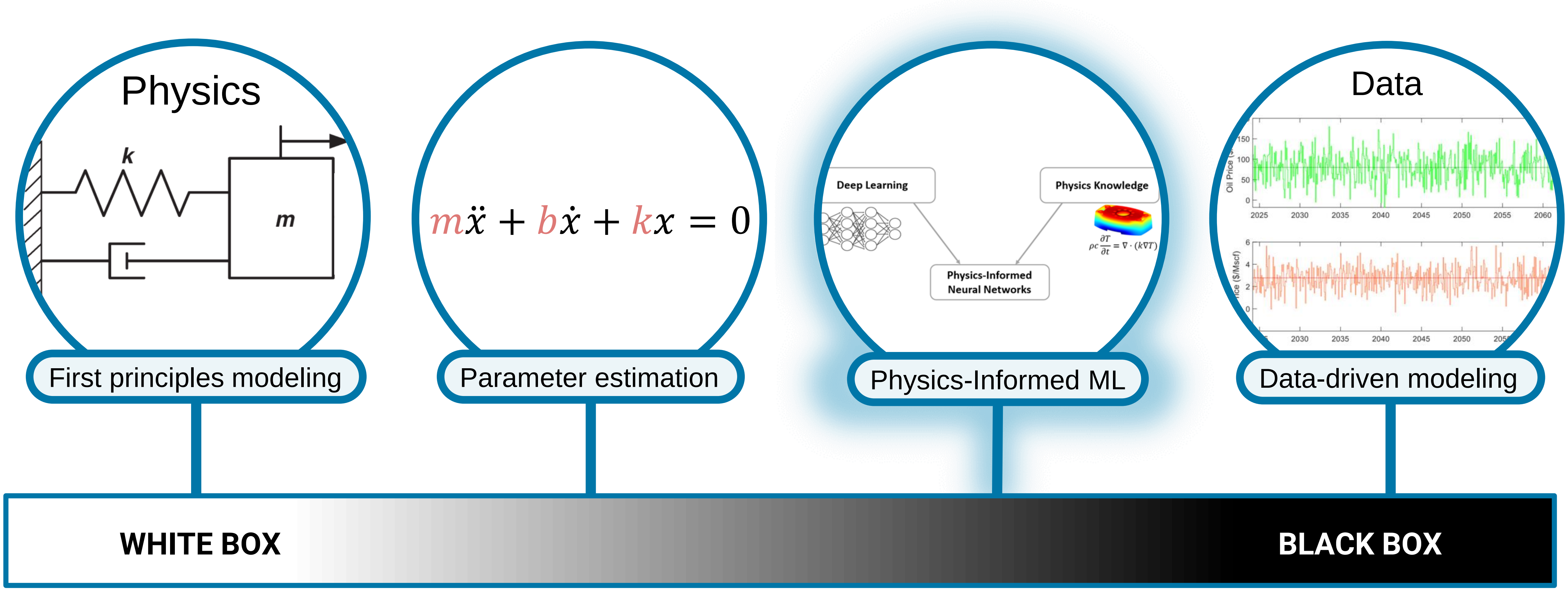


[Link to User Story]

Cummins Uses AI-Based Reduced Order Modeling to Predict Engine Performance and Emissions

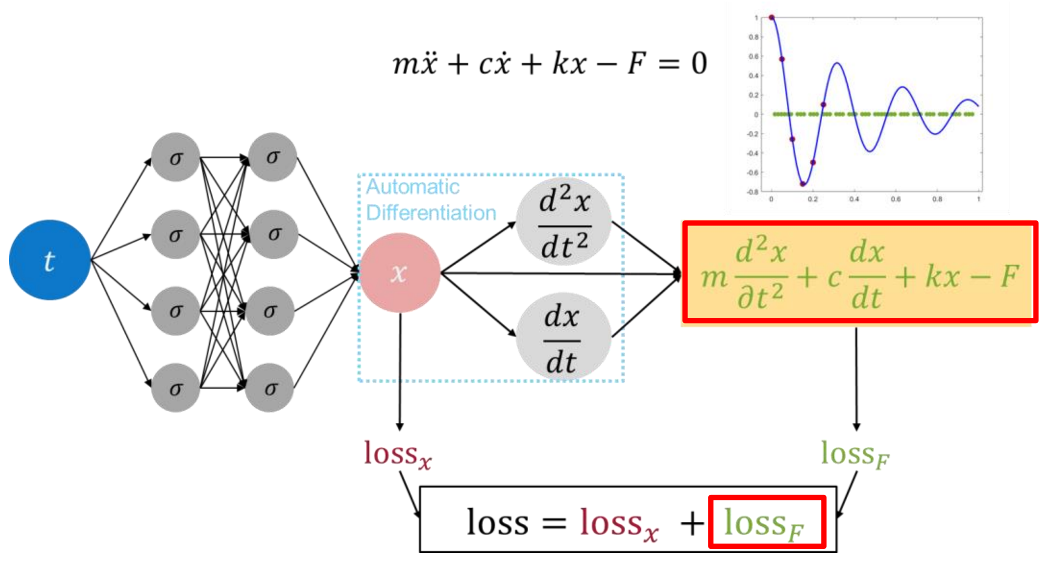
Cummins used LSTM-based neural networks to reduce engine cycle simulation run times to one-eighth of real time.

Where do you get the information to create a model?



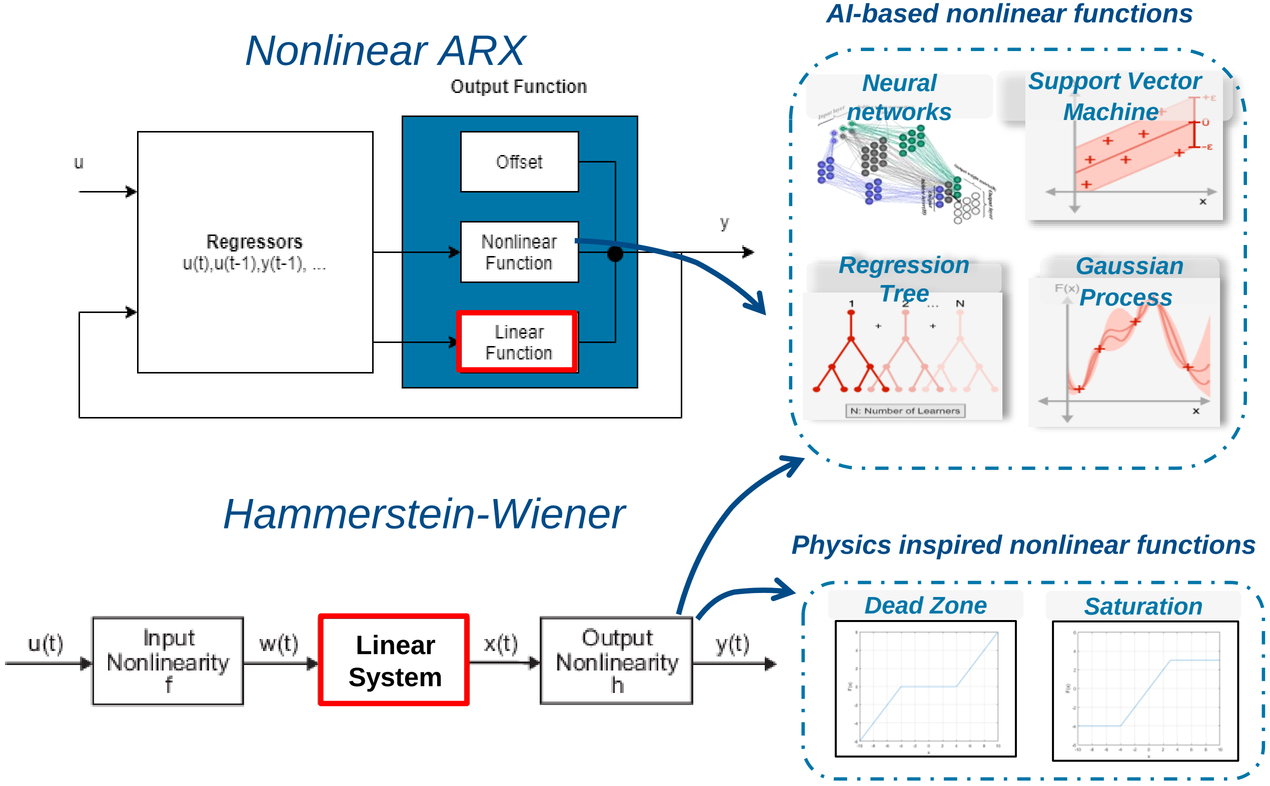
Physics-Informed Machine Learning techniques let you incorporate your understanding of physics to enhance machine learning methods

Loss Functions



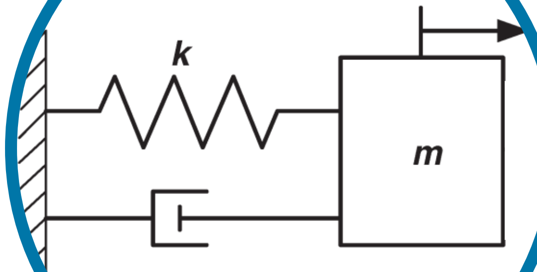
Physics-Informed Neural Networks (PINNs)

Model Architectures

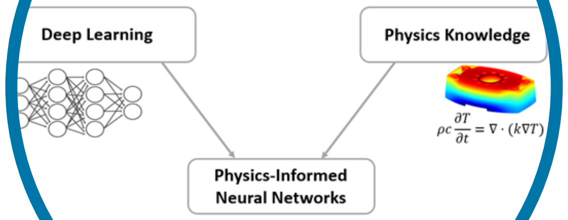


Where do you get the information to create a model?

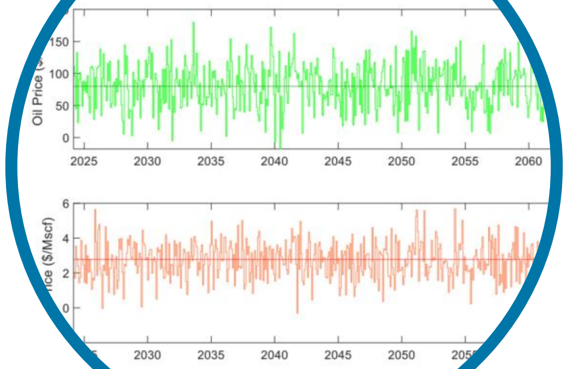
Physics



$$m\ddot{x} + b\dot{x} + kx = 0$$



Data



First principles modeling

Parameter estimation

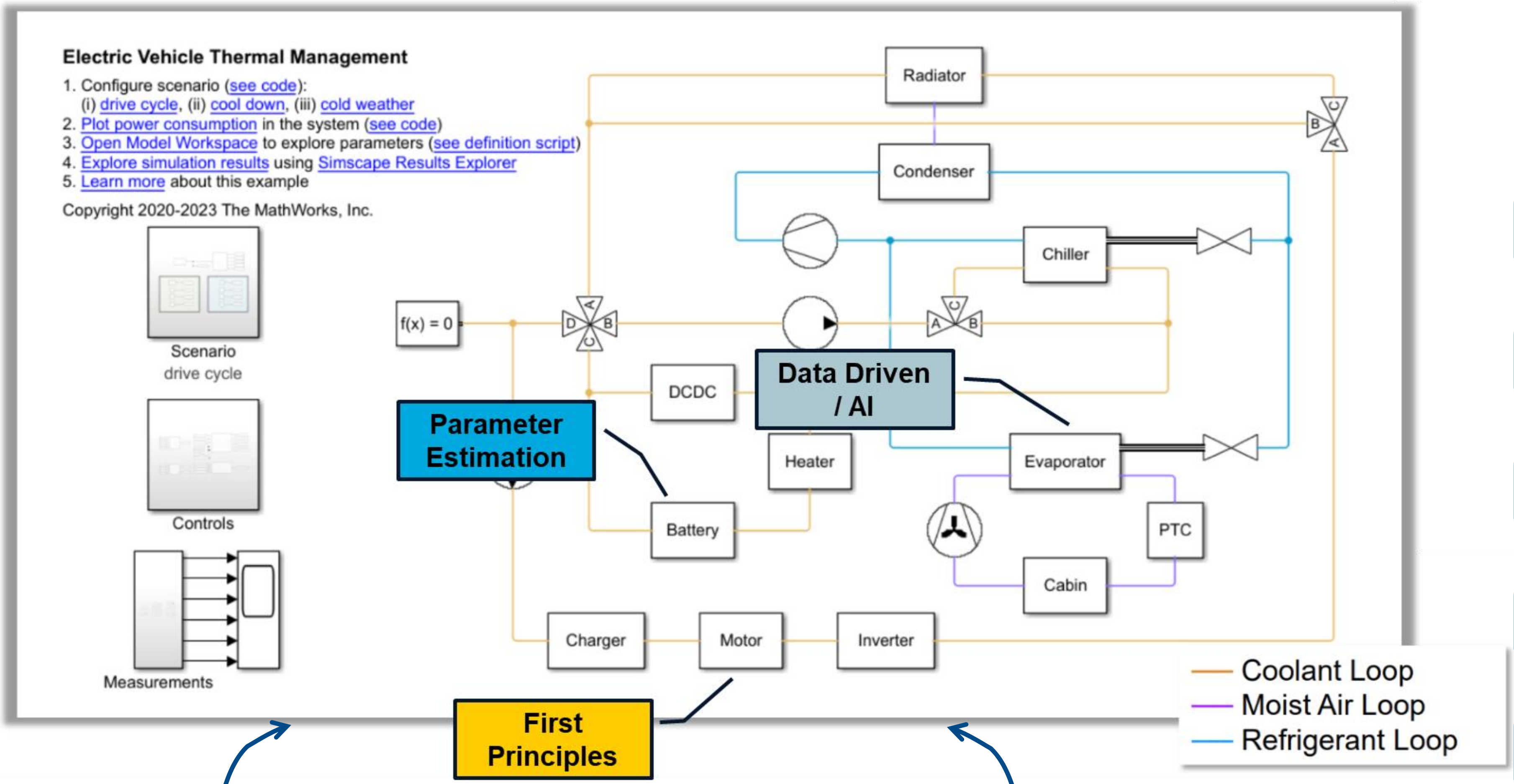
Physics-Informed ML

Data-driven modeling

WHITE BOX

BLACK BOX

Models come together for a purpose



3rd party full-order models (FEA/CFD/CAE)

Deep learning models from PyTorch/TensorFlow

Desktop Simulation

Hardware-in-the-Loop Testing

System-Level Analysis

Control Design

Design Optimization

and more ……

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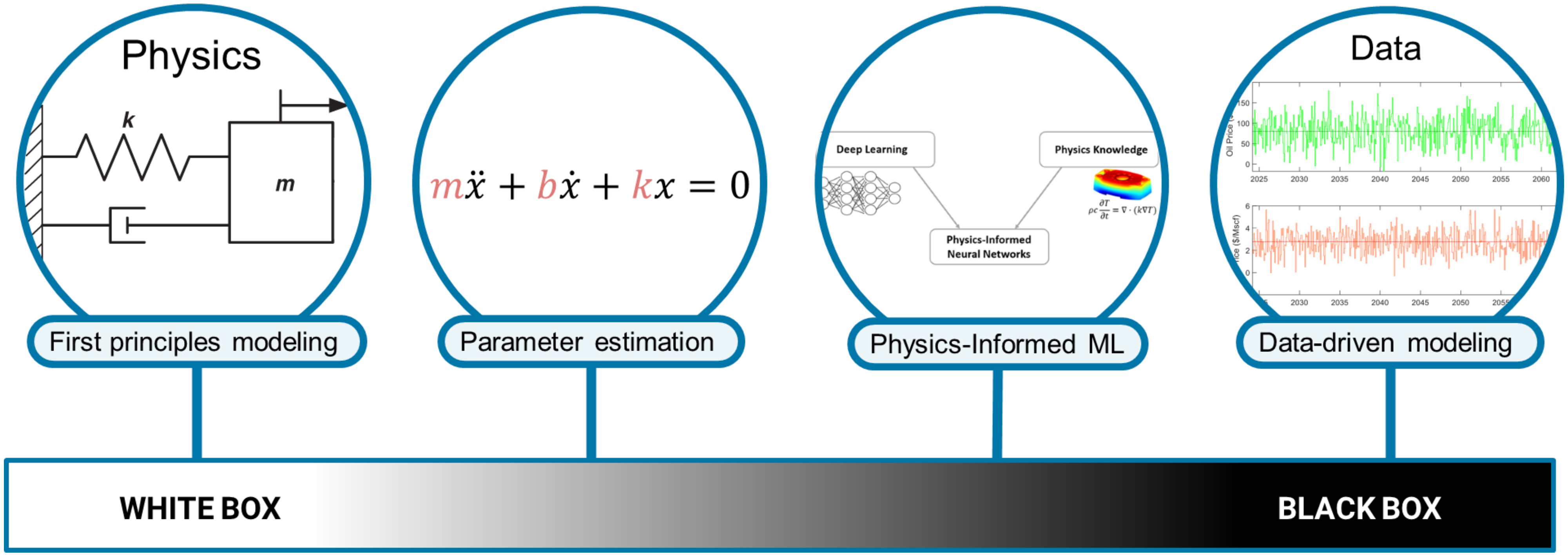
There are advantages across the modeling spectrum



Advantages

- Have clear (explainable) physical meaning
- Do not require data engineering

Advantages

- Identify models when first-principles models are difficult to derive
- Reduce complexity

Check out this poster for a larger list of modeling capabilities