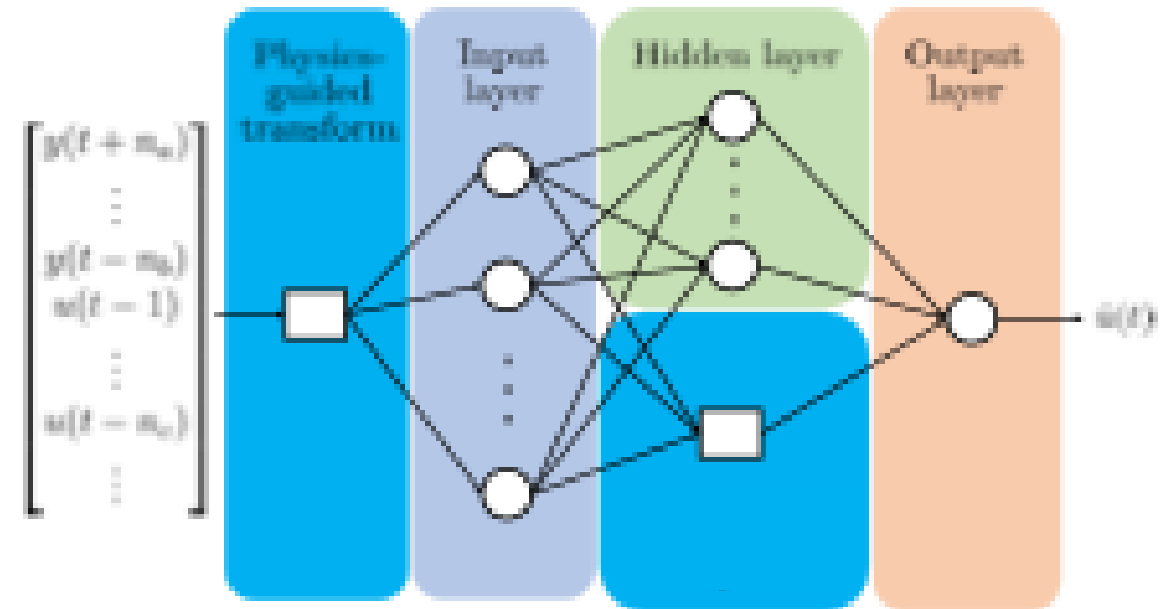
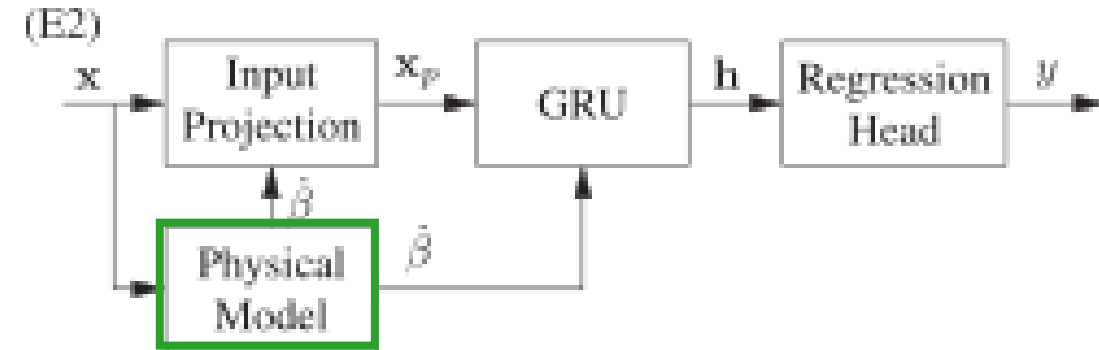


Physics-Guided Inputs, Data and Representations

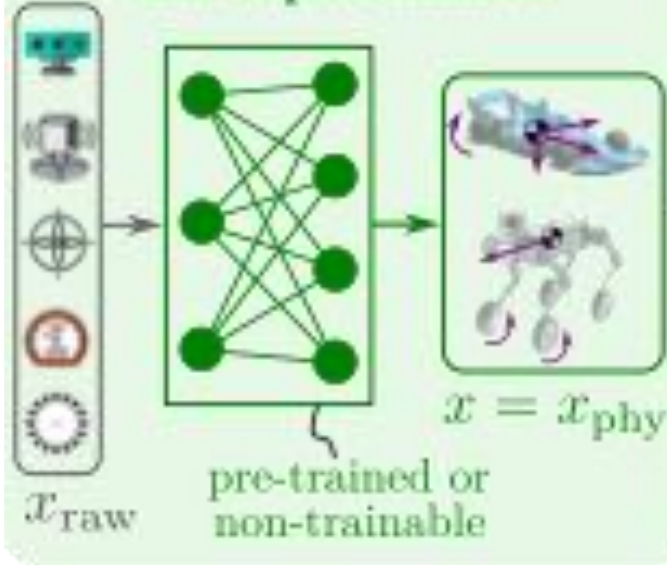
Dr. Mattia Piccinini &
Prof. Gastone Pietro Rosati Papini

University of Trento &
Technical University of Munich,
Autonomous Vehicle Systems Lab



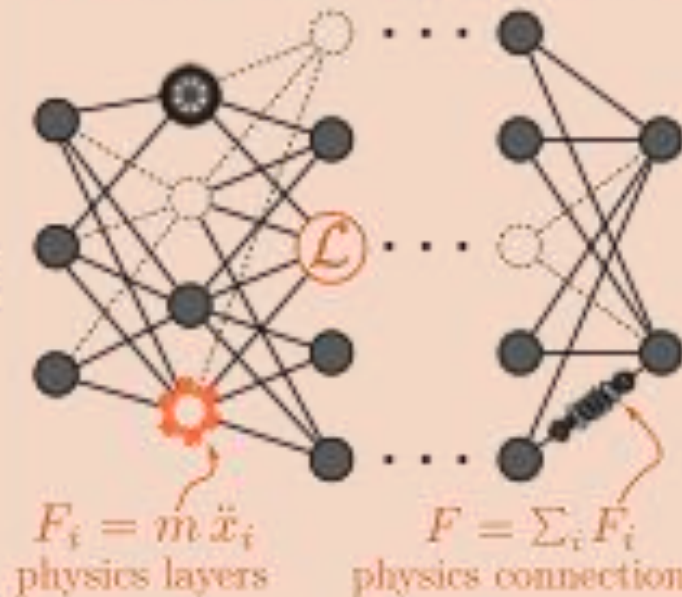
Physics-Guided Learning: Positioning

Physics-Guided Inputs, Data, and Representations



x

Physics-Encoded Architecture



y

Physics-Informed Loss

$$\mathcal{L} = \mathcal{L}_{\text{physics}} + \mathcal{L}_{\text{data}}$$

bound. cond.

$$\|x(0) - x_0\|^2$$

$$\|F - m \ddot{x}\|^2$$

physics models

$$\|F - m \ddot{x}\|^2$$

ODE/
PDE

$$\|\dot{x} - f(x, u)\|^2$$

What Does Physics-Guided Learning Include?

Embedding **physics insights** into:

- Input features
- Data representations
- Training data selection / generation



ASME
SETTING THE STANDARD

ASME Journal of Computing and Information Science in Engineering
Online journal at:
<https://asmedigitalcollection.asme.org/computingengineering>



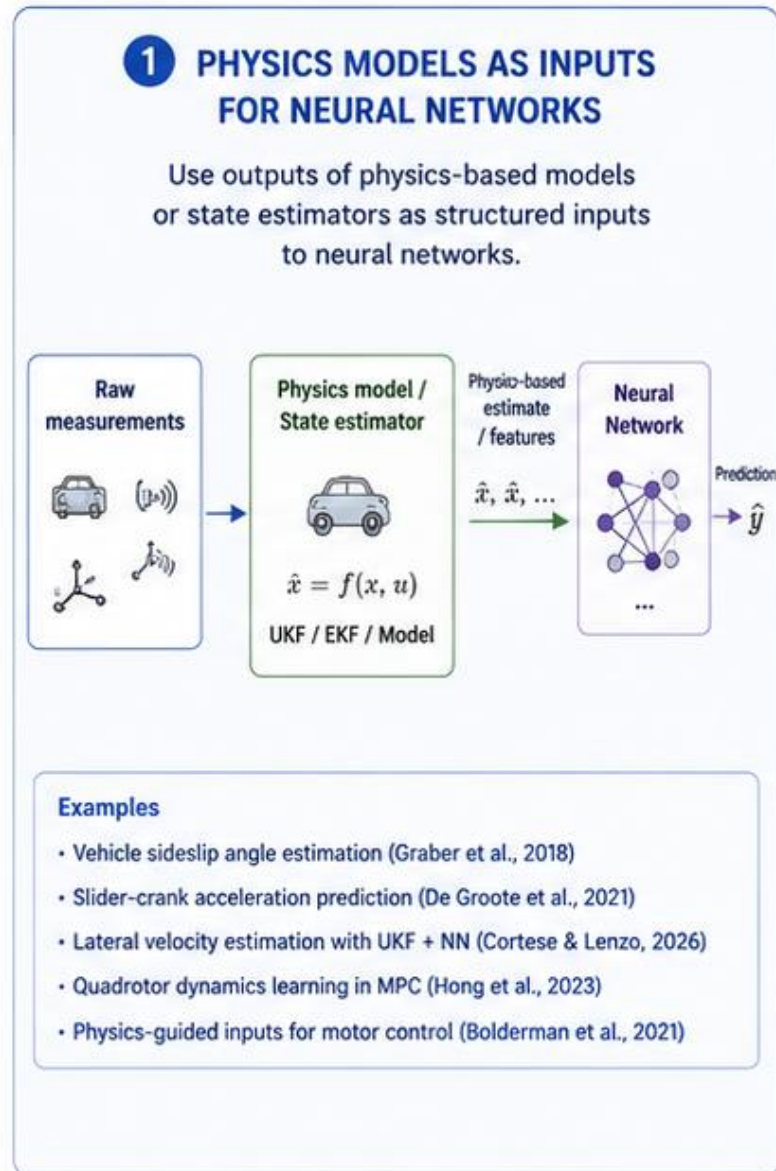
Salah A. Faroughi¹
Geo-Intelligence Laboratory,
Ingram School of Engineering,
Texas State University,
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e-mail: salah.faroughi@txstate.edu

Nikhil M. Pawar
Geo-Intelligence Laboratory,
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Texas State University,
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Célio Fernandes
Geo-Intelligence Laboratory,

Physics-Guided Physics-Informed, and Physics-Encoded Neural Networks and Operators in Scientific Computing: Fluid and Solid Mechanics

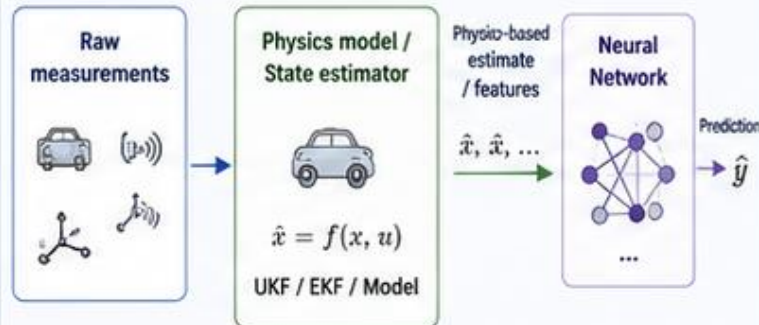
Physics-Guided Learning: Multiple Classes



Physics-Guided Learning: Multiple Classes

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Use outputs of physics-based models or state estimators as structured inputs to neural networks.



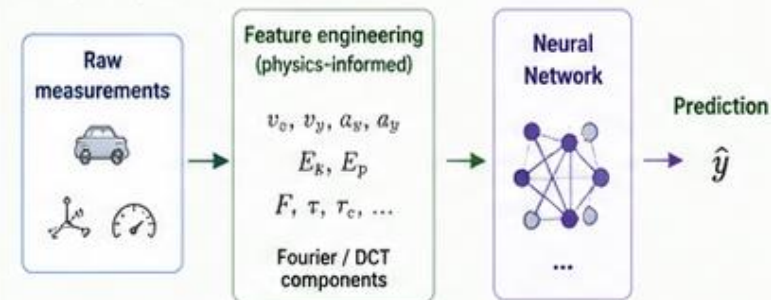
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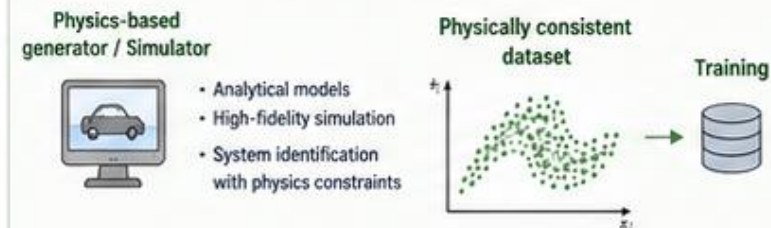
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Design physics-informed input features and generate or select training data that obey physical laws.

A) Physics-guided features



B) Physically consistent training data



Examples

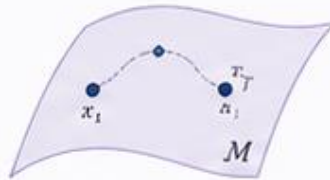
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Physics-Guided Learning: Multiple Classes

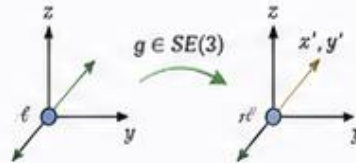
3 GEOMETRIC LEARNING

Respect geometric structures (manifolds, symmetry, SE(3) transforms, graphs) in data and models.

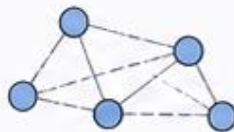
Manifold / Lie group learning



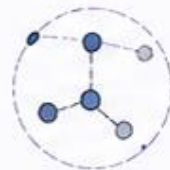
SE(3) equivariant models



Graph / Interaction learning



Geometric constraints in latent space



Examples

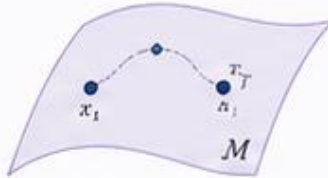
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Physics-Guided Learning: Multiple Classes

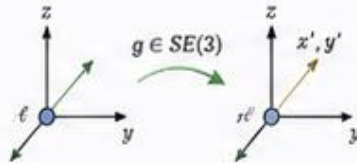
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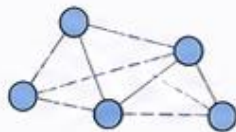
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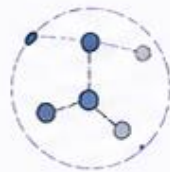
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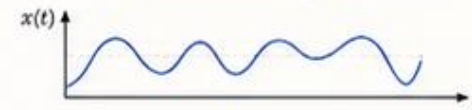
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4 FREQUENCY-DOMAIN LEARNING

Transform data to the frequency domain to capture dynamics across time and space scales.

Time-domain signals



Transform
(DCT / FFT)

Frequency-domain representation



Modeling in frequency domain



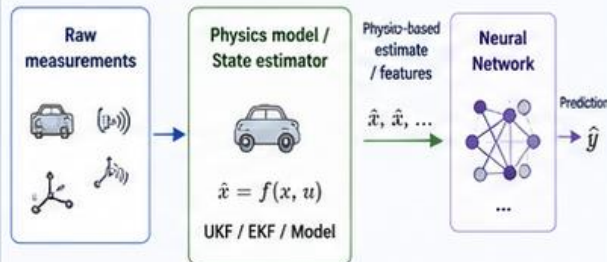
Examples

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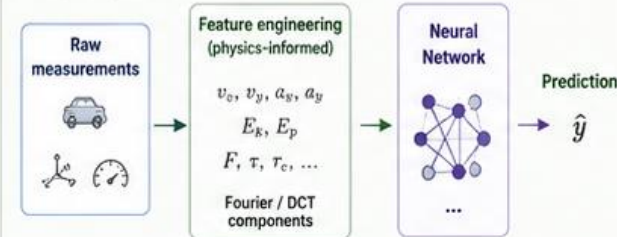
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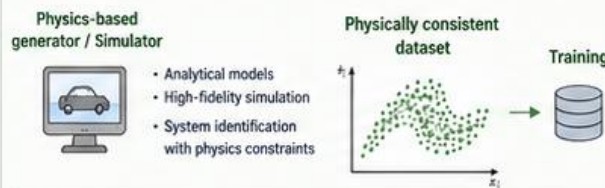
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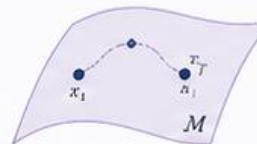
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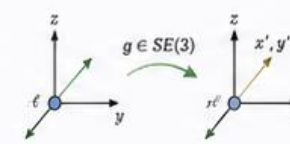
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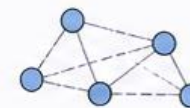
Manifold / Lie group learning



SE(3) equivariant models



Graph / Interaction learning



Geometric constraints in latent space

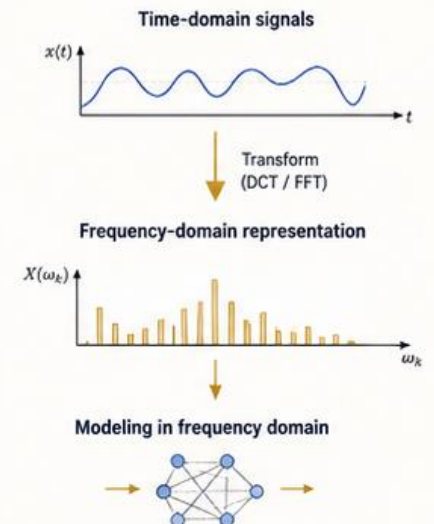


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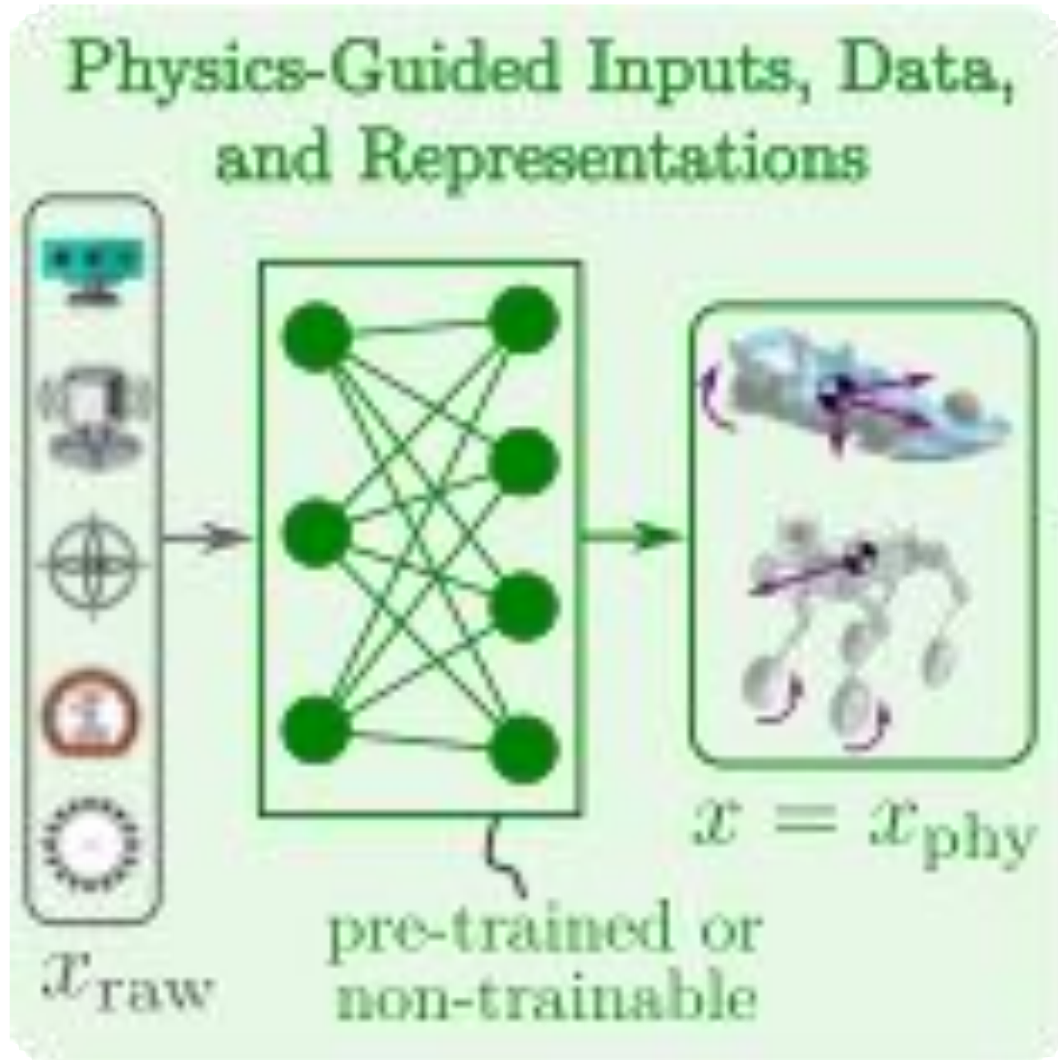
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Examples

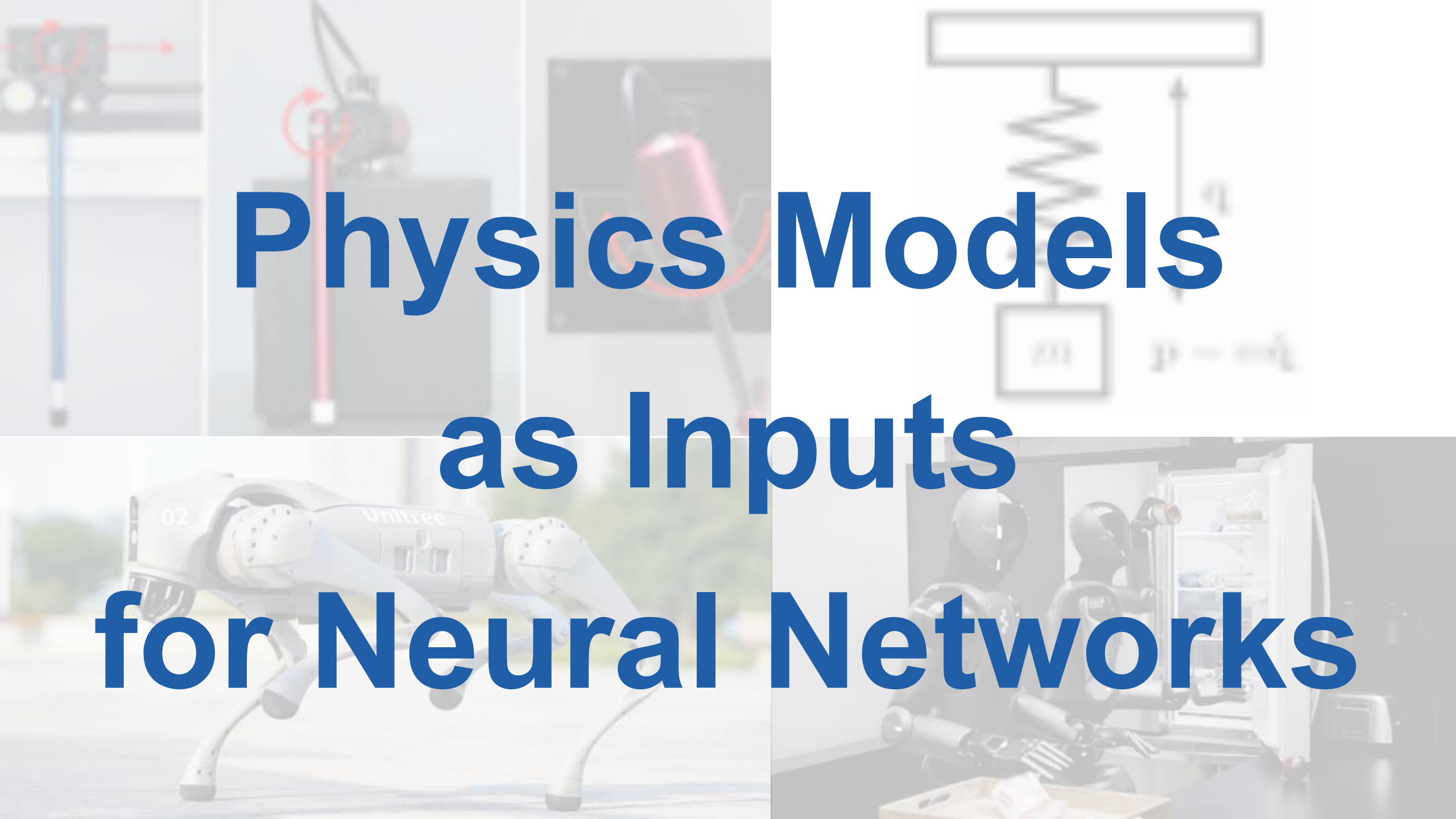
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Physics-Guided Learning: Remark



Physics-guided operations are **pre-trained**
or **non-trainable**:

if they contain NNs, these are ***not* trained**
together with the main model

The background is a collage of four images. Top-left: A close-up of a robotic joint with a red arrow indicating rotation. Top-right: A diagram of a mass-spring system with a mass 'm' and displacement 'q', with the equation $p = m\dot{q}$ below it. Bottom-left: A white quadruped robot, labeled 'Unitree' and '02', in motion. Bottom-right: A robotic arm in a laboratory setting, with a person in a lab coat and helmet visible in the background.

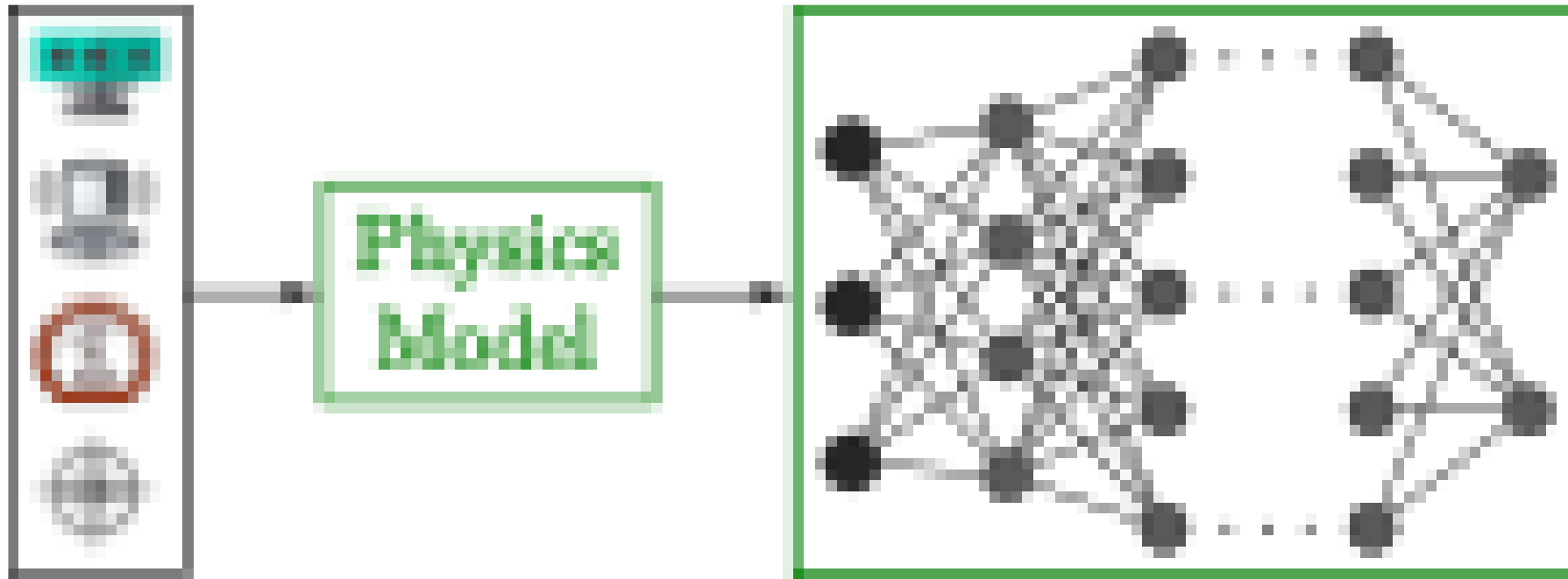
Physics Models

as Inputs

for Neural Networks

Physics Models as Inputs for Neural Networks

Idea: Use **physics-based modes** to generate input features for machine learning models
→ Constrain learning to a **physically consistent** space

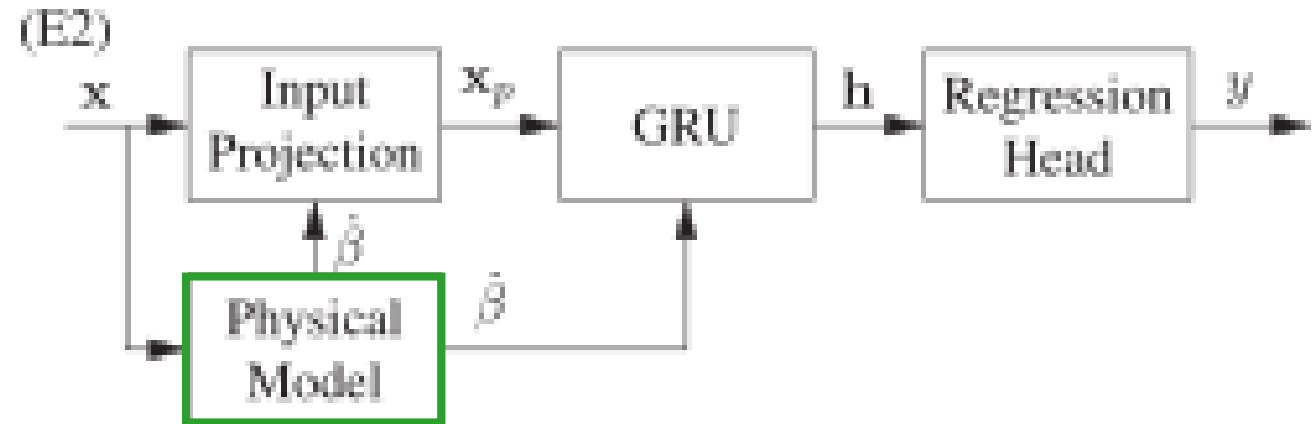
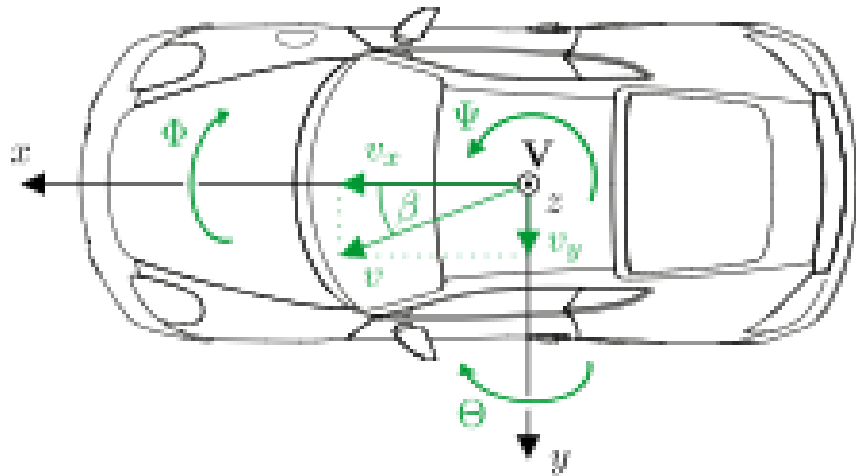


Physics Models as Inputs for Neural Networks - Examples

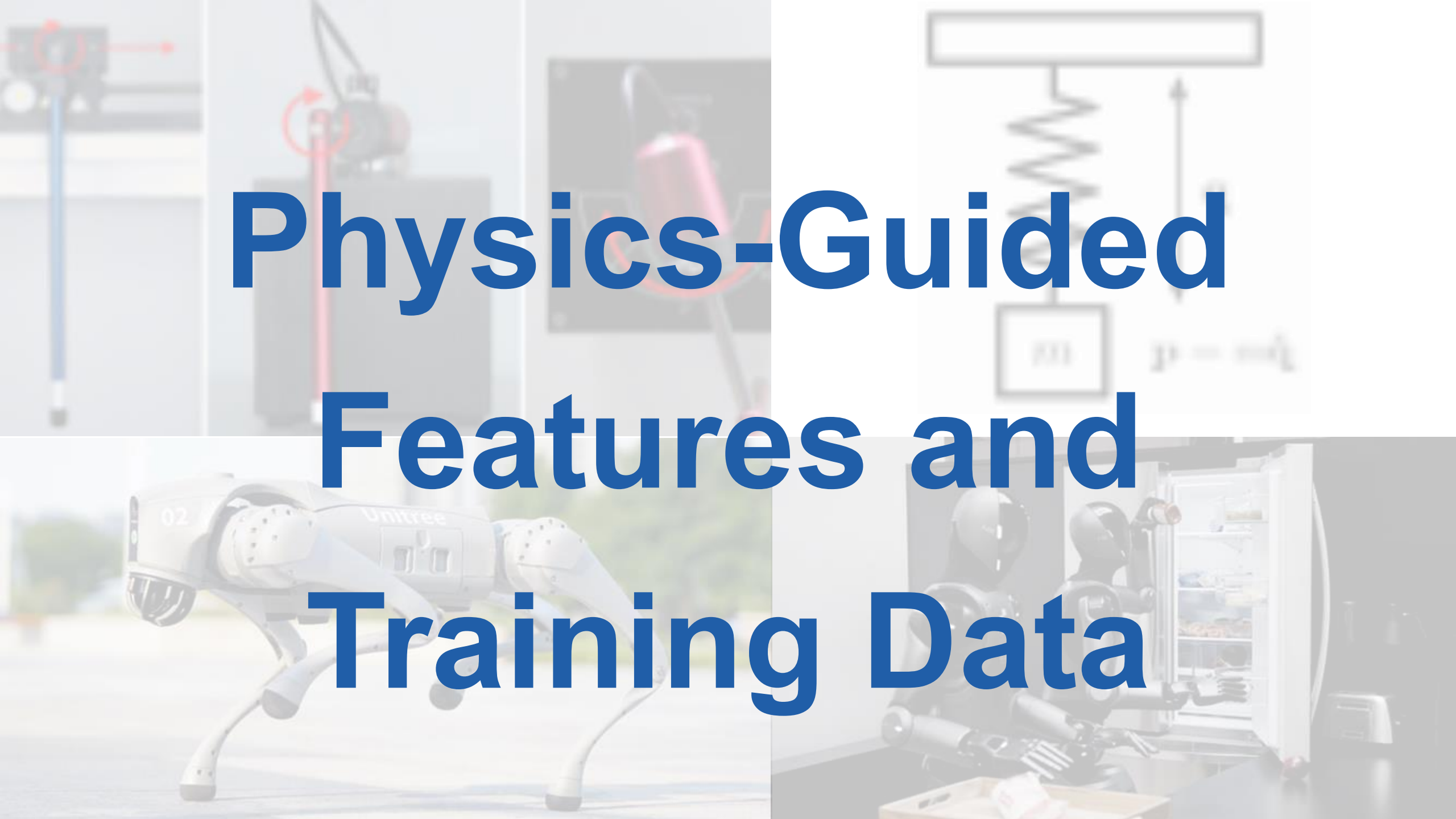
Vehicle sideslip angle (β) estimation

Physics-guided NN design:

- **Physics-based estimator** of $\dot{\beta}$, then fed to a Gated Recurrent Unit (**GRU**) NN
- **Outperforming** the same NN without physics-guided inputs
- **Outperforming** a purely physics-based model



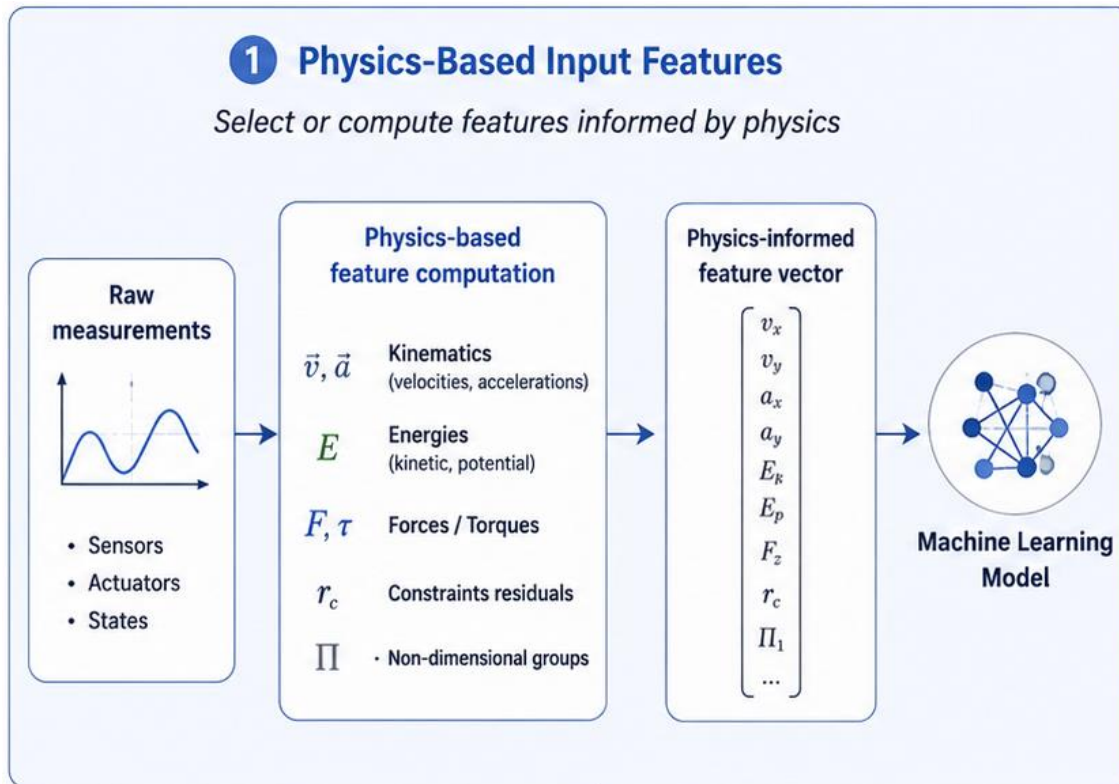
Physics-Guided Features and Training Data



Physics-Guided Features and Training Data

Idea:

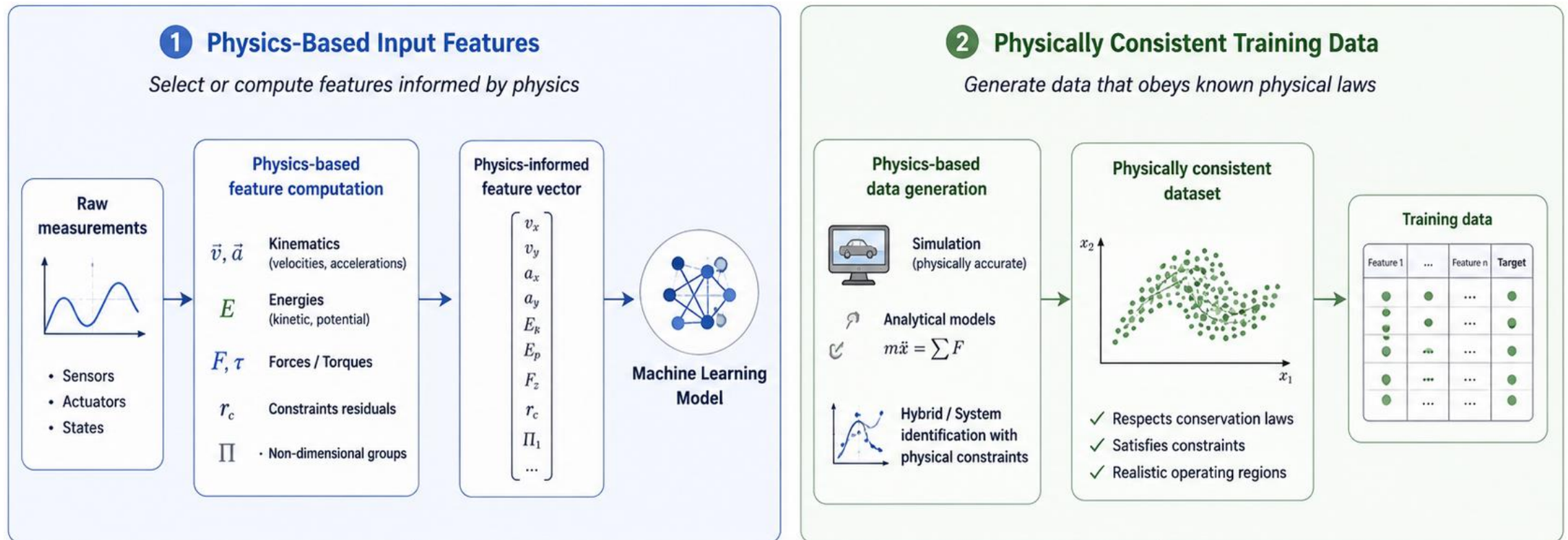
- Select / compute **physics-based input features** for machine learning models



Physics-Guided Features and Training Data

Idea:

- Select / compute **physics-based input features** for machine learning models
- Generate physically consistent **training data**

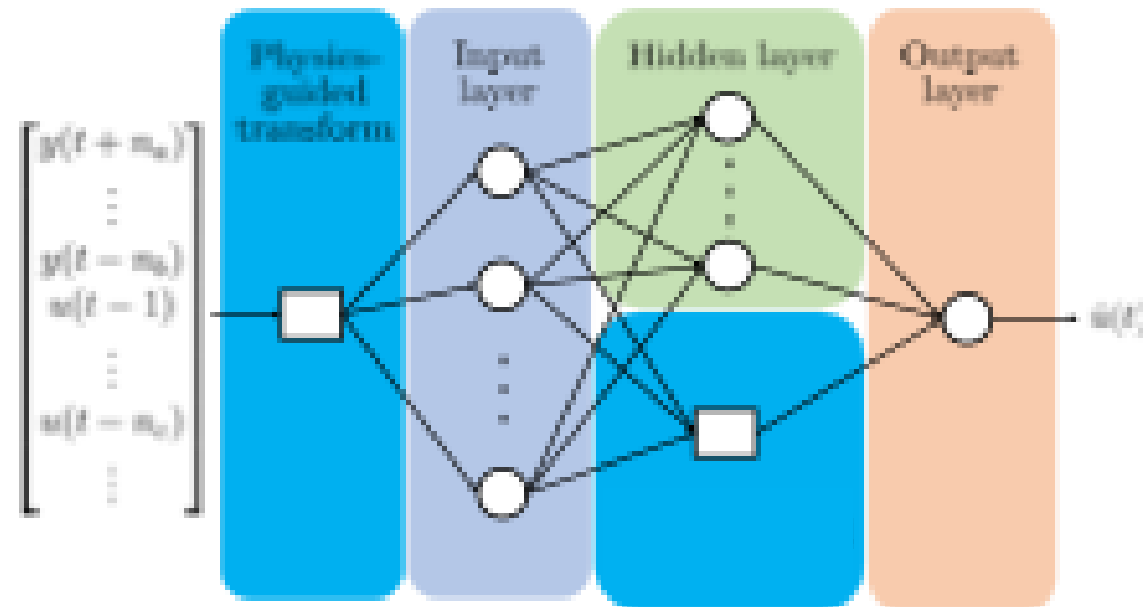


Physics-Guided Features and Training Data - Examples

Feedforward control of linear motors: Compute force $\hat{u}(t)$ to track a desired position y

Physics-guided NN design:

- Linear friction depends on position y , velocity $\dot{y}$, $\text{sign}(\dot{y}) \rightarrow$ use them as **additional NN inputs**
- **Outperforming** the same NN without physics-guided input features



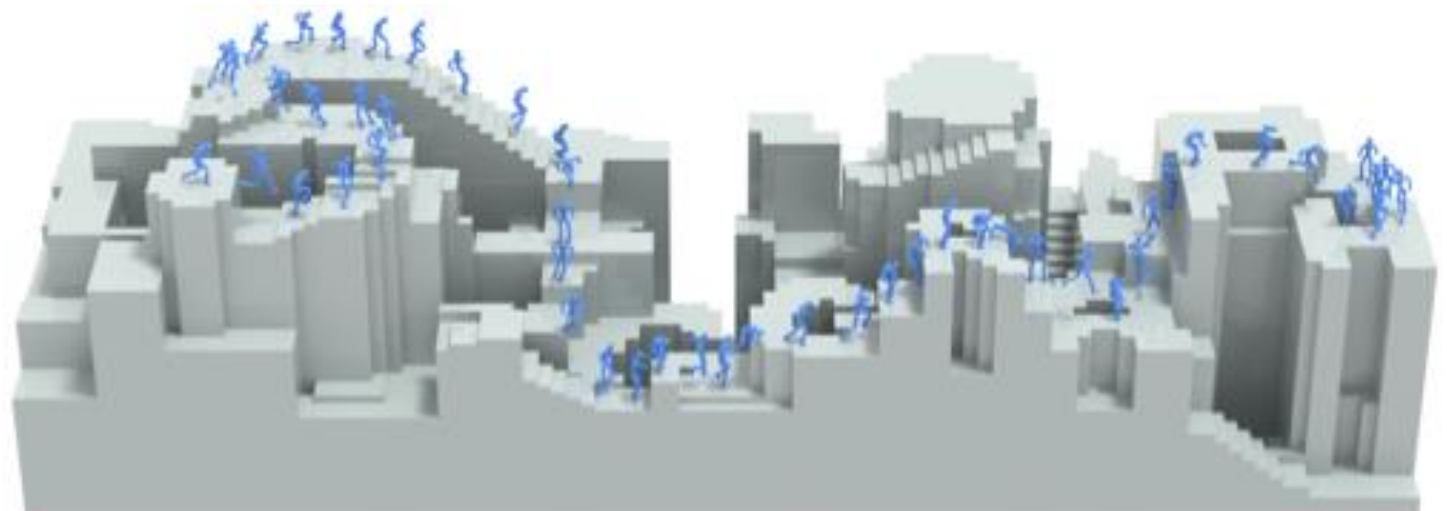
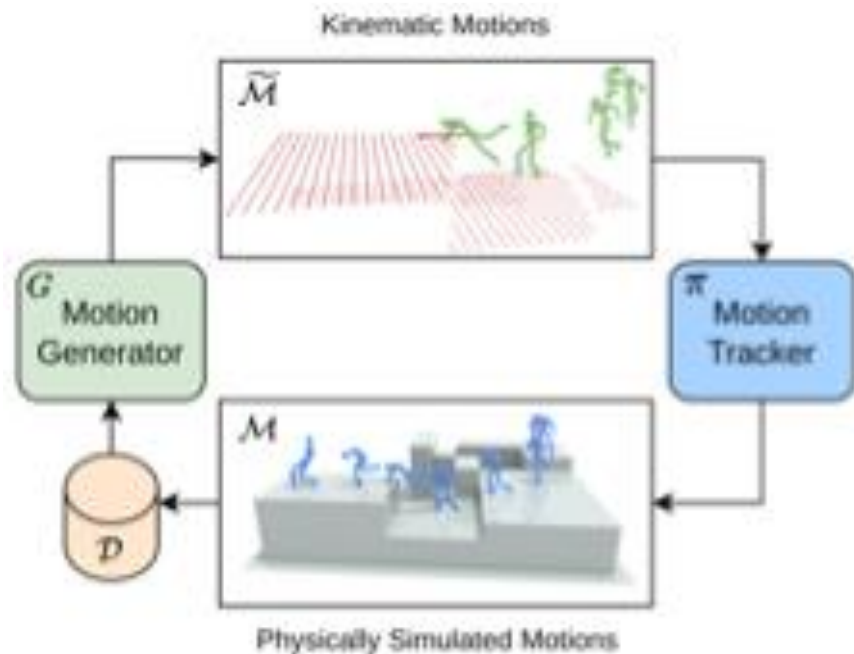
$$\hat{u}(t) = f_{\text{PGNN-1}} \left(\theta, y(t), u(t-1), y(t), y(t-1), \dot{y}(t), \dot{y}(t-1), \text{sign}(\dot{y}(t)), \text{sign}(\dot{y}(t-1)) \right).$$



Physics-Guided Features and Training Data - Examples

Generating human motions in **parkour** scenarios in Isaac Gym

- **Diffusion model** to generate motions
- **Physics-based tracking controller** to make the motions physically consistent
- The corrected motions are recycled as **training data** for the **diffusion model**



Questions & Discussion

