Workshop on Physics-informed Machine Learning for Modeling, Control, and Optimization

At the 2024 American Control Conference (ACC 2024)

July 10-12, 2024 | Vancouver, Canada

The Organizers

Thomas Beckers
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Technical University of Darmstadt

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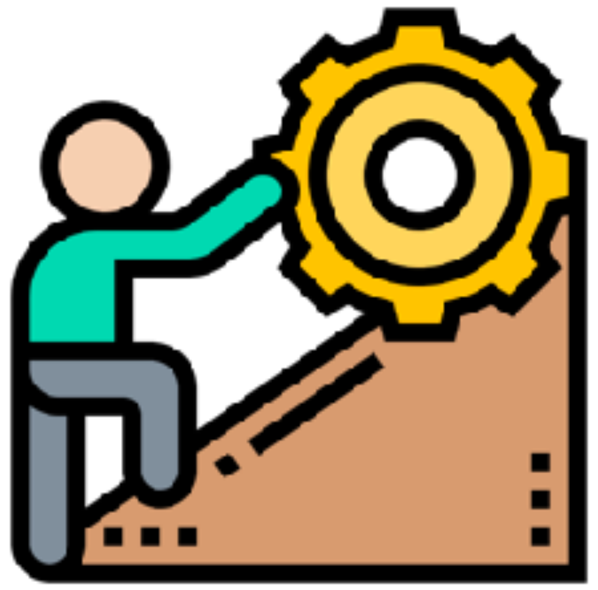
Goals

To provide insight into recent advances in the field of physics-informed machine learning for control and optimization with hands-on tutorials



To sketch some of the open challenges and opportunities in physics-informed machine learning

Speakers are encouraged to share slides on
piml4control.github.io/PIML-ACC2024

Schedule morning

All times are in **EST (UTC-5)**

- **[08:30-08:45]:** Workshop Opening
- **[08:45-09:30]:** Invited Talk 1 **Thomas Beckers (Vanderbilt University)**
- **[9:30-10:15]:** Invited Talk 2 **Giulio Evangelisti / Sandra Hirche (Technical University of Munich)**
- **[10:15-10:45]:** Coffee Break
- **[10:45-11:30]:** Invited Talk 3 **Sivaranjani Seetharaman (Purdue University)**
- **[11:30-12:15]:** Invited Talk 4 **Rolf Findeisen (TU Darmstadt)**
- **[12:15-13:45]:** Lunch (on your own; no sponsored lunch provided)

Schedule afternoon

- **[13:45-15:15]:** Open-source Code Tutorial Session I
- **[15:15-15:45]:** Coffee Break
- **[15:45-17:15]:** Open-source Code Tutorial Session II
- **[17:15-17:30]:** Closing Remarks and Discussion

PyEPO - Bo Tang [13:45-15:15]

NeuroMANCER - Jan Drgona [15:45-17:15]

Why do we need to enhance ML?

Informative Data	Low	Medium	High
High	Machine Learning	Physics-enhanced Machine Learning	Physics-enhanced Machine Learning
Medium	Physics-enhanced Machine Learning	Physics-enhanced Machine Learning	Physics-enhanced Machine Learning
Low	Physics-enhanced Machine Learning	Physics-based Modeling	Physics-based Modeling

Physics knowledge

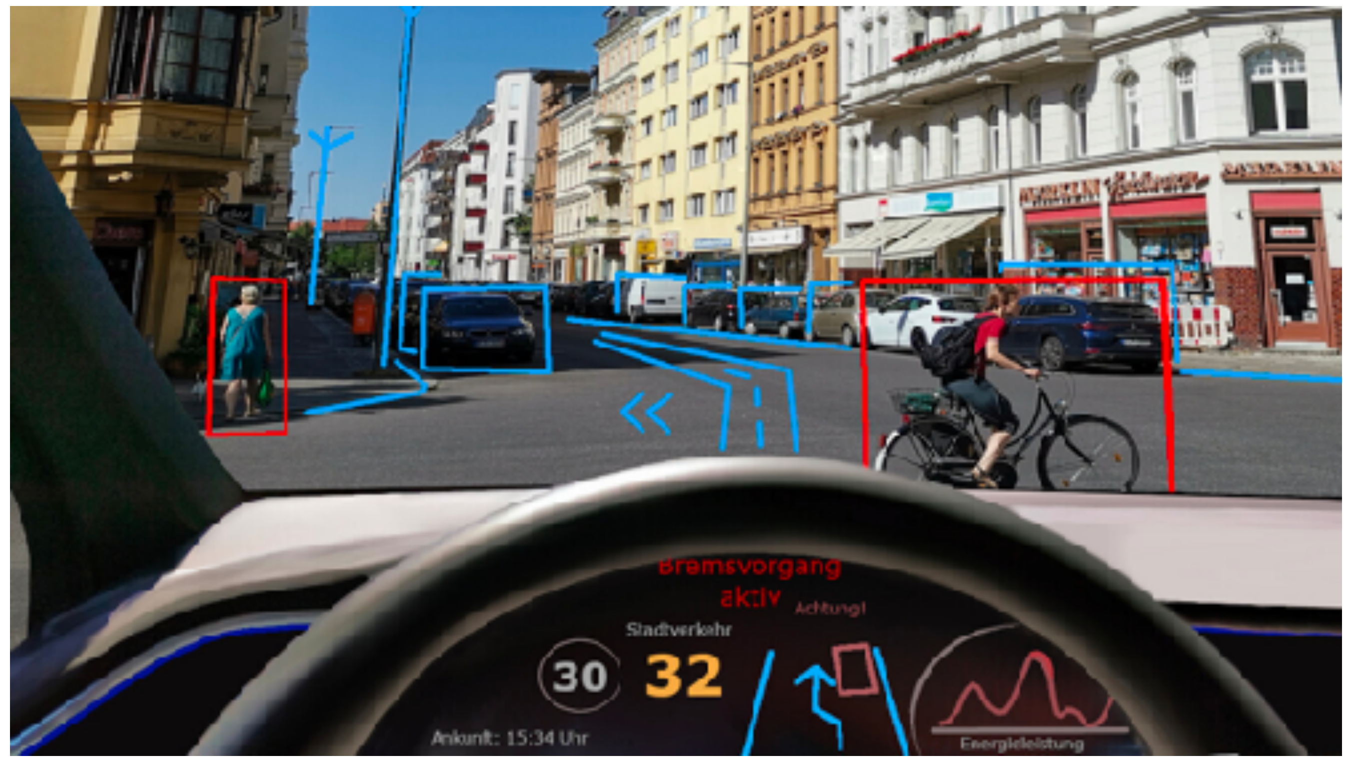
Physics knowledge to

- **enable generalization (small data)**
- **enforce physics (large data)**

Purely data-driven methods

But we need more for

Autonomous driving



[Electric Motor Engineering]

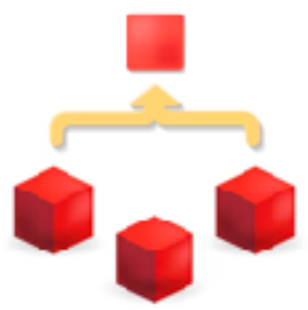
Human-robot collaboration

[Ars Electronica]

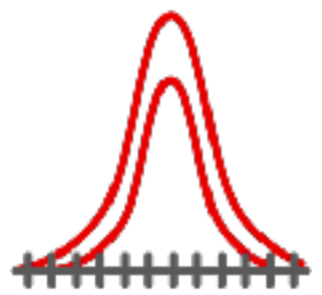
Power grids

[Chris Hunkeler]

Goals of PIML



Overcoming poor generalization performance
Removing physically inconsistent or implausible predictions
(Improving control strategies, interaction models,…)



Uncertainty Quantification
(Physics, data, learning model, deductible, irreducible)

Providing **explainable** and **interpretable** inference

Informing physics
(Identification of unknown governing physics equations)

Domain knowledge

Prior knowledge: observational, empirical, physical, mathematical

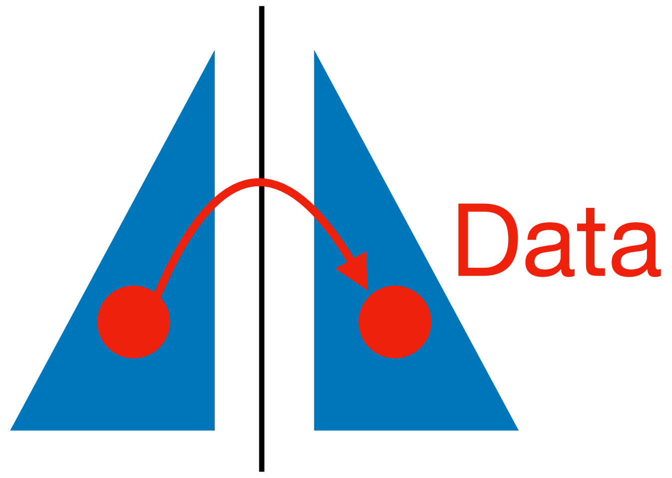
Small, heterogenous, gappy, noisy data

Multi-fidelity data

Dealing with wrong models, corrupted data, uncertainties and non-informative data

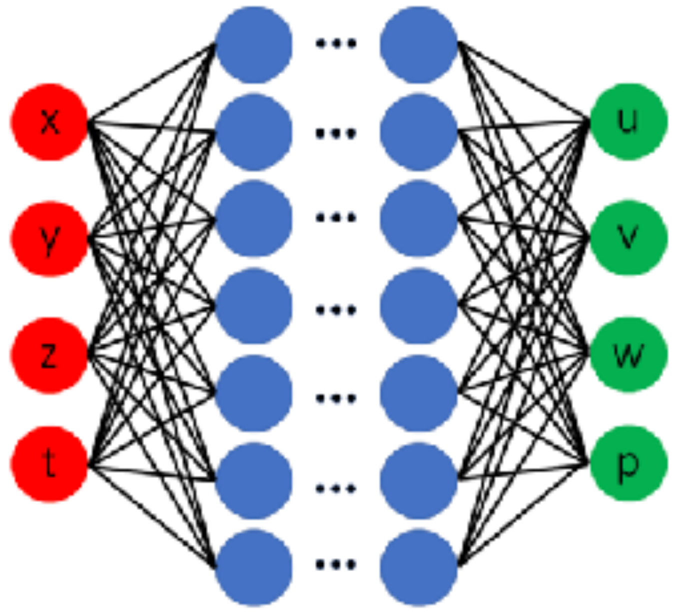
How to incorporate physics?

Observational bias
Introducing data that embody underlying physics



Symmetry

Learning bias
Inference/learning algorithm selection, loss function, optimization constraints



$$Loss = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$$

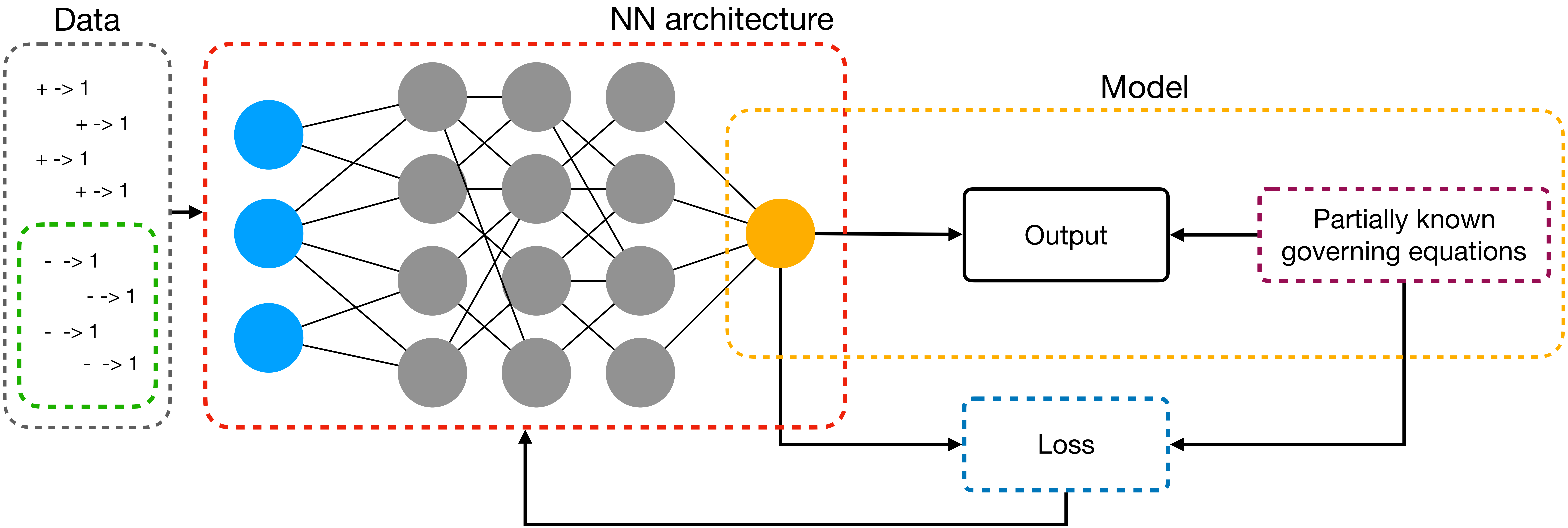
Inductive bias
Incorporate prior assumptions and physical constraints

Conservation laws

Discrepancy bias
Including “terms” from partial knowledge of the model

$$\dot{x} = Ax + Bu + f(x, u)$$

Example



Observation bias: Introducing data that embodies underlying physics

Inductive bias: Prior assumptions and physical constraints

Learning bias: Physics based loss function, optimization algorithm

Discrepancy bias: Introducing data that embodies underlying physics

Do we need different models?

Complexity

LTI system

Nonlinear, time-varying system

Multi-scale, multi-physics, nonlinear, …

Amount of data

Sparse identification

Bayesian models

Neural networks

Purpose

Identifying unknown physics/ governing equations?

Data efficiency

Interpretability

Modeling/Control/Optimization

Development of digital twins

There is not “the one” model

Opportunities in control

Optimization

Constructing surrogate PIML models for the hard-to-optimize physics-based optimization problems or cost functions

Modeling & Control

Modeling of high dimensional and distributed physics in multi-physics systems.

Generation of structured PIML controllers for multicomponent systems with awareness of interconnections

Assurances

Providing safety and performance guarantees for a broad class of learning-based control methods.

T. X. Nghiem *et al.*, "Physics-Informed Machine Learning for Modeling and Control of Dynamical Systems," *2023 American Control Conference (ACC)*, 2023

Challenges

How to

- unify the terminology of PIML models? (enhanced, informed, constrained, guided, encoded)
- avoid training failures of PIML models getting stuck in local optima
- detecting & removing inappropriate physics bias
- verify methods for PIML to be scaled up for large-scale systems
- reduce the computational requirements without sacrificing accuracy

- balance between physics-driven and data-driven based modeling and optimization
- quantify minimal data requirements for training of PIML models and controllers
- quantify the uncertainty and modeling errors for PIML-based models
- effectively select representative training data for sampling-based PIML approaches
- guarantee stability and safety of a real-world system in closed-loop with PIML-based controllers

T. X. Nghiem *et al.*, "Physics-Informed Machine Learning for Modeling and Control of Dynamical Systems," *2023 American Control Conference (ACC)*, 2023

More resources

Machine Learning and the Physical Sciences

Annual Workshop at NeurIPS
https://ml4physicalsciences.github.io/2023/

IOP Institute of Physics

Workshop on Physics Enhancing Machine Learning in Applied Mechanics

Annual Workshop organized by the IOP
https://iop.eventsair.com/asm2023/

AIRES 4: Machine Learning For Robust Digital Twins

Annual Workshop organized by US National Laboratories
https://aires.ornl.gov/

DDPS Webinar (*in California time*)

Seminar series
https://www.librom.net/ddps.html#ddps-webinar-in-california-time

Physics-informed machine learning meets engineering seminar series

Seminar series organized by the Alan Turing Institute
https://www.turing.ac.uk/events/phi-ml-meets-engineering

CDC 2024

2024 Conference on Decision and Control

December 16-19, 2024

Allianz MiCo, Milan Convention Centre, Italy