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Towards a digital twin for underwater systems

A Meta-Learning-based Approach

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Båstad 2023-10-12, NATO STO AVT-369

Challenge at hand

- In late 2022: Saab Light Weight Torpedo (SLWT) delivered to the Swedish Defence Materiel Administration (FMV)
- Modular design and optimal operation for the Baltic sea, maximizing availability through electric propulsion
- BUT: batteries degrade over time
- THEREFORE: desired high-fidelity models of physical assets to monitor condition
- SO THAT: the battery usage and future design may be optimized

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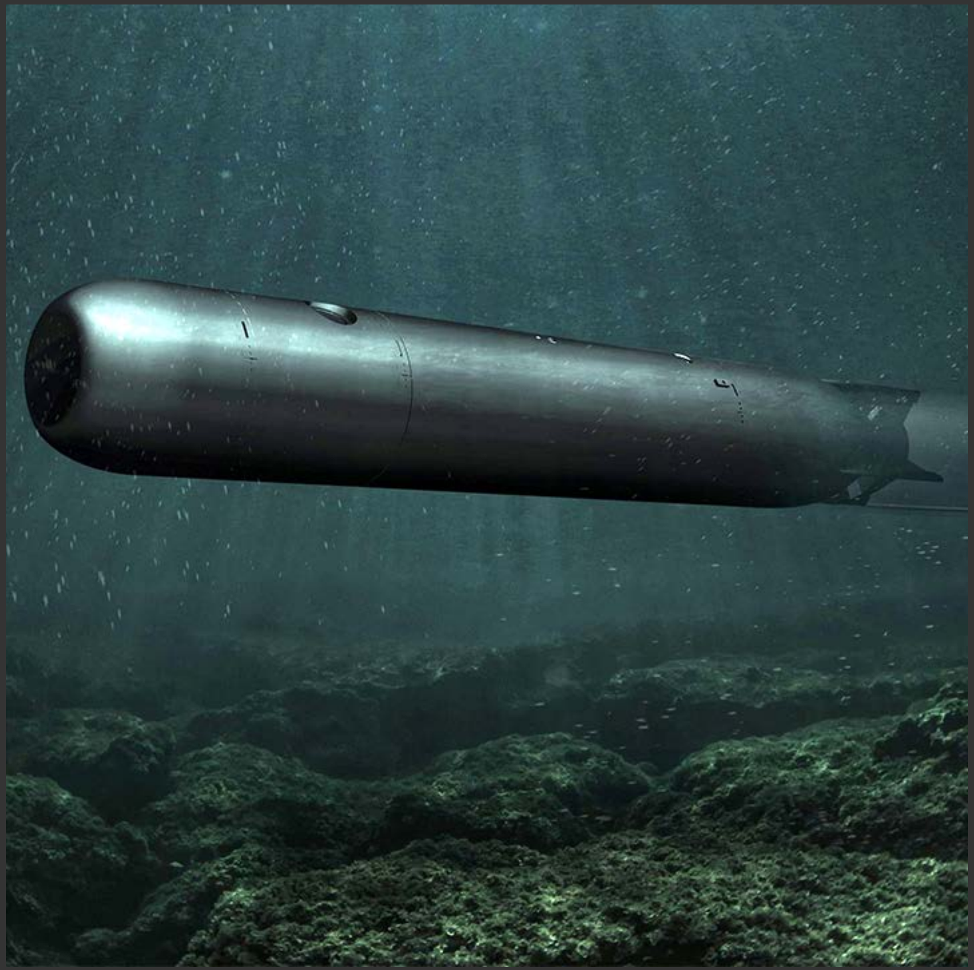
Optimal operation, predictive maintenance & effective design-support

Battery degradation prediction



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Saab Dynamics

- Underwater, Missiles and Ground Combat
- Linköping and Karlskoga (+ new office in Karlstad)
- Focus on Swedish market, but also three international strategic markets: Australia, the UK and the U.S.
- Wide range of novel and legacy systems

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Saab Light Weight Torpedo

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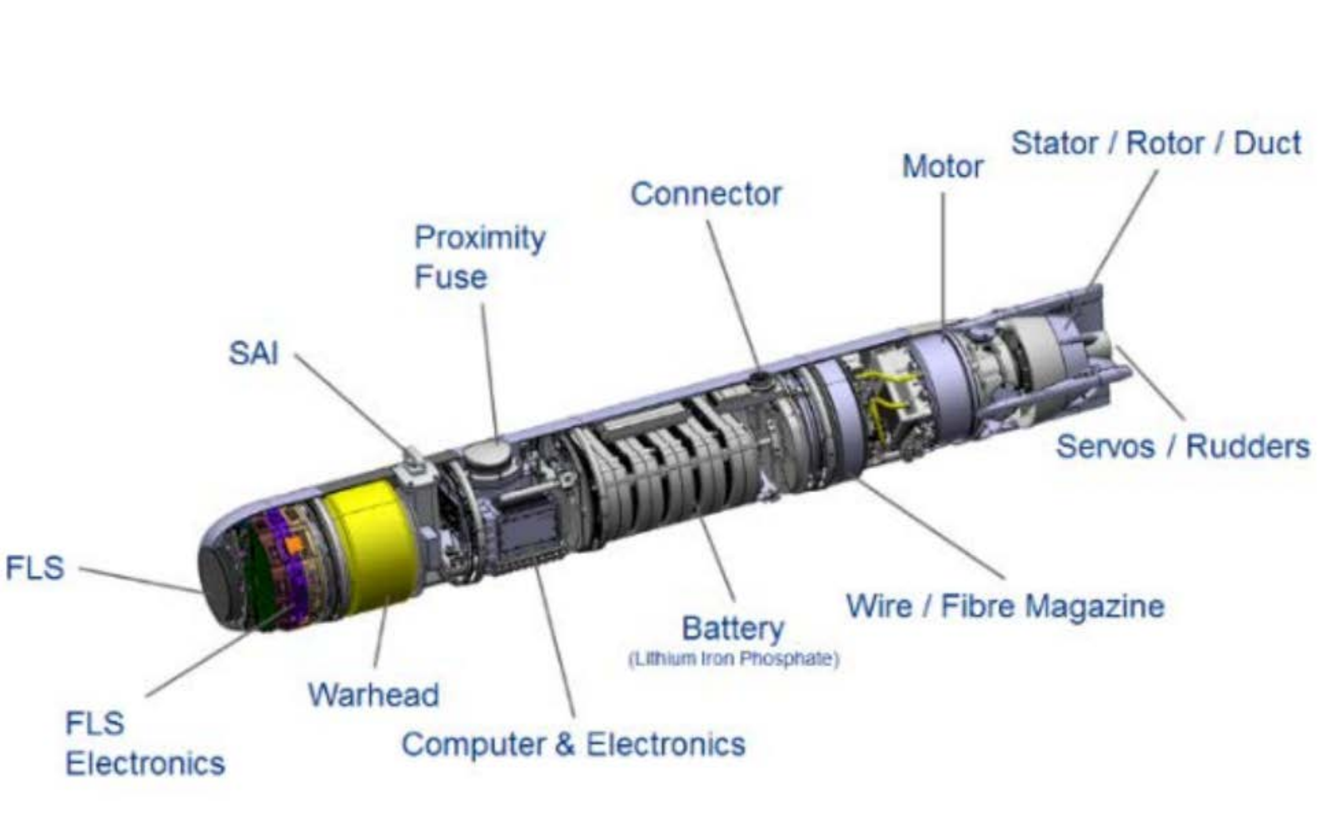
Brackish
Ø54m
Atlantic
SZTOKHOLM
HIUMA
SAREMA
GŁĘBIA LANDSORT 459m
GOTLANDIA
OLANDIA
GŁĘBIA GOTLANDZKA 220m
KŁAJPEDA
KALININGRAD
GDYNIA



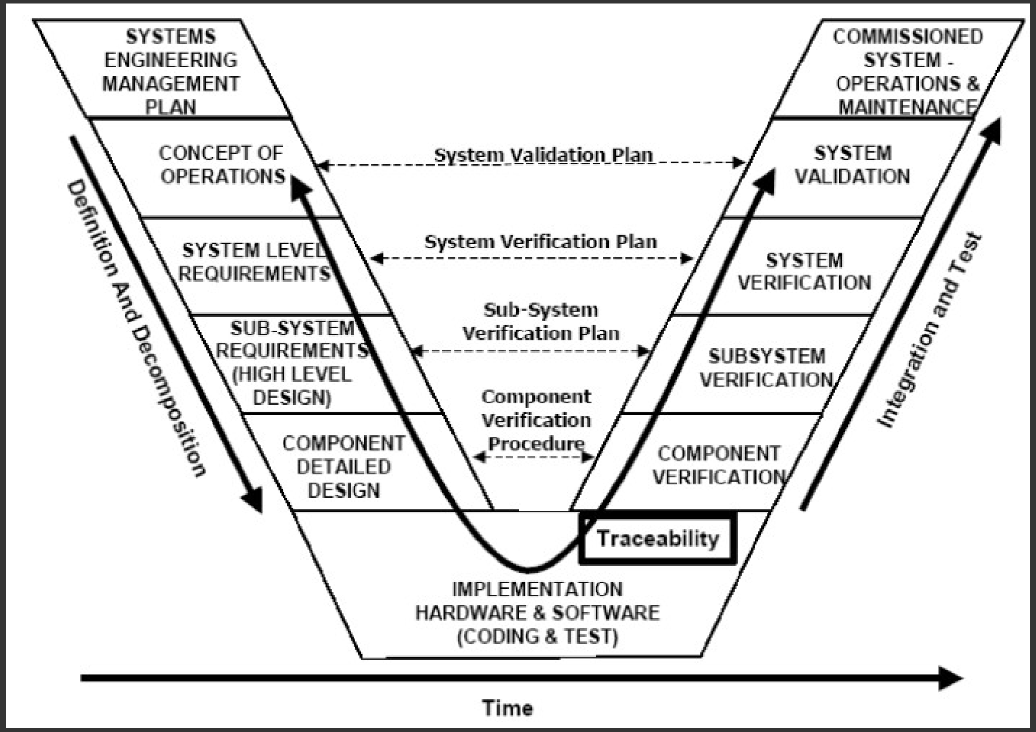
Saab Light Weight Torpedo

SAAB

SLWT models to support operation

Large range of design and ILS models on multiple levels of abstraction, scope and detail:

- Hydrodynamic Model: Water flow, currents, and pressure dynamics.
- Sensor and Detection Model: sonar and other sensor data, target detection and tracking.
- Communication Model: protocols, reliable data transmission in challenging conditions.
- Target Behavior Model: adaptive defense strategies.
- Control and Actuation Model: control algorithms (autonomous systems)
- **Missing: digital counterpart to physical assets**



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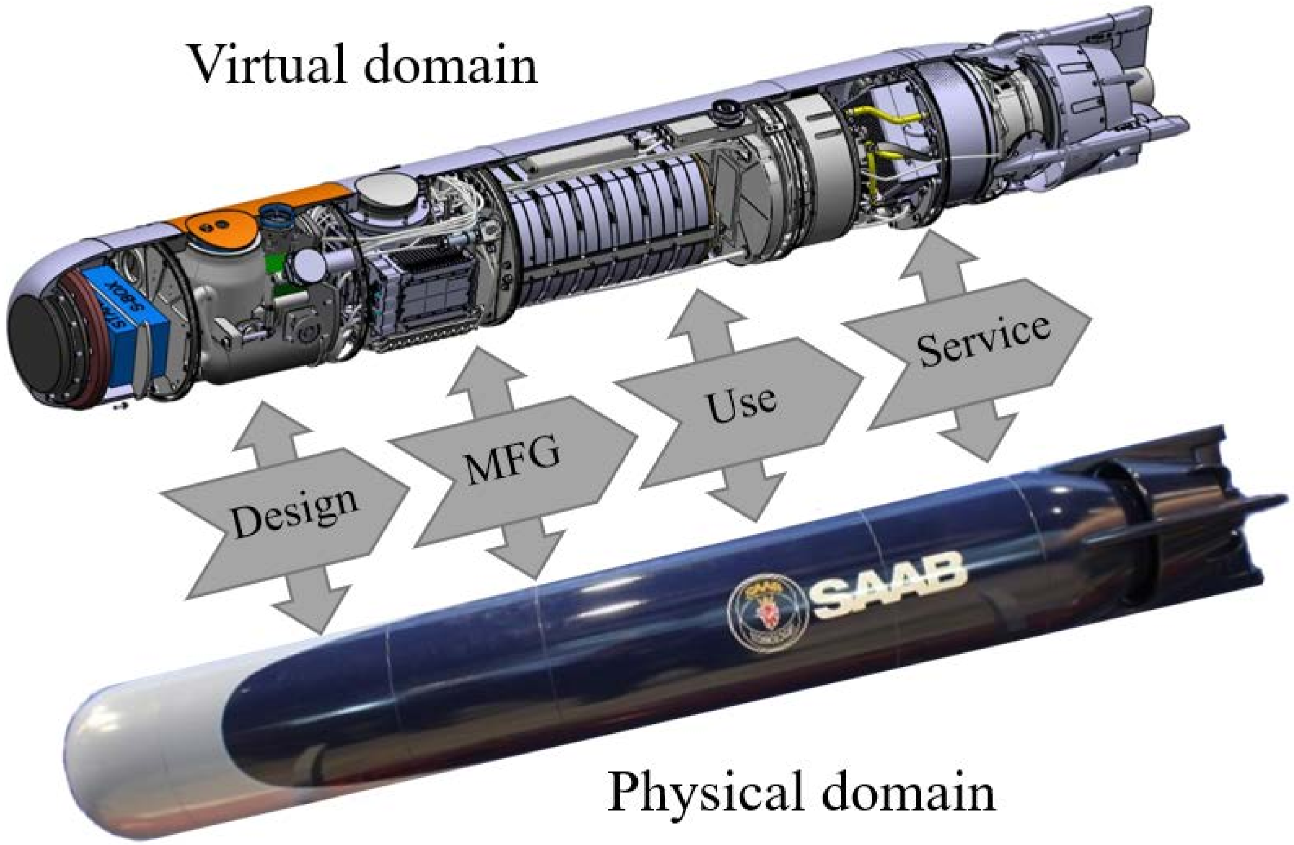
End goal



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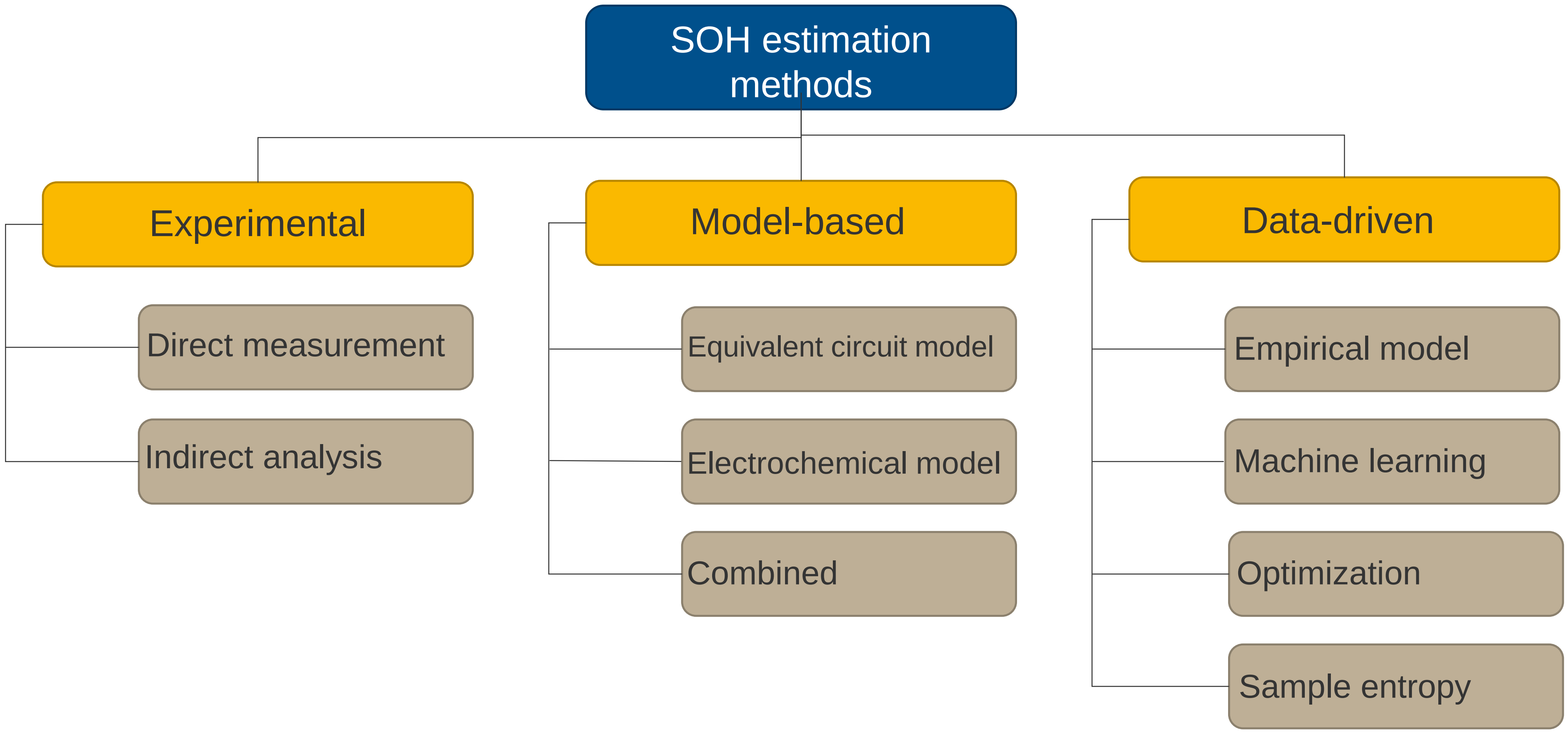
Battery modelling



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Data-scarce Digital Twins?

The Challenge: Low Data Access

- **Limited Training Data:** Insufficient data for accurate model creation
- **Reduced Effectiveness:** Hinders the capabilities of digital twins
- **Consequences:** Impacts decision-making, testing, and analysis

Root Causes:

- **Classified Environments:** Security concerns restrict data usage.
- **Cost and Resources:** Expensive and resource-intensive data collection.
- **Rapid Technology Evolution:** Obsolescence of existing data.

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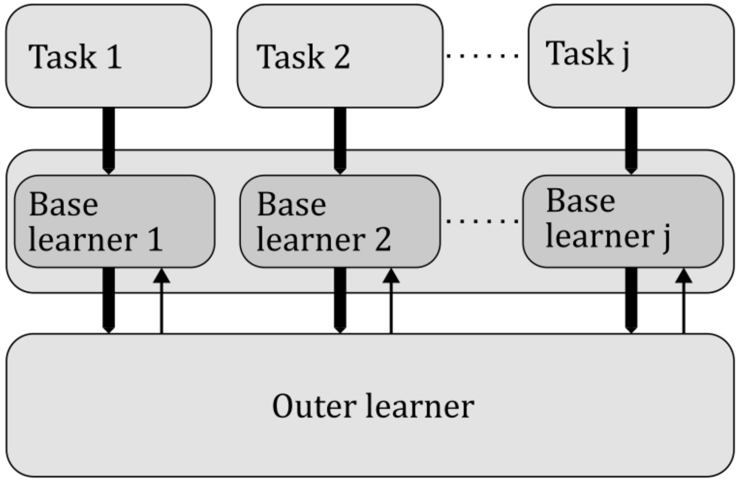
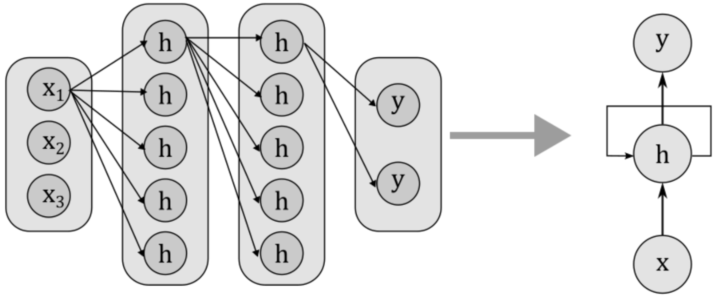
Meta Learning

- Focuses on “learning how to learn”
- Enables models to acquire new knowledge and adapt quickly to different tasks
- Key components: tasks, models, and meta-learners.
- Learns from multiple tasks to improve generalization abilities
- Few-shot learning is a common application of meta-learning, where models excel with minimal examples.
- Meta-learning algorithms include Reptile and Model-Agnostic Meta-Learning (MAML)
- Plays a pivotal role in enabling AI systems to continuously improve and adapt in dynamic environments
- Research is ongoing
- Here:
  - Outer learner: Model Agnostic Meta Learning, MAML
  - Inner learner: Recurrent Neural Network





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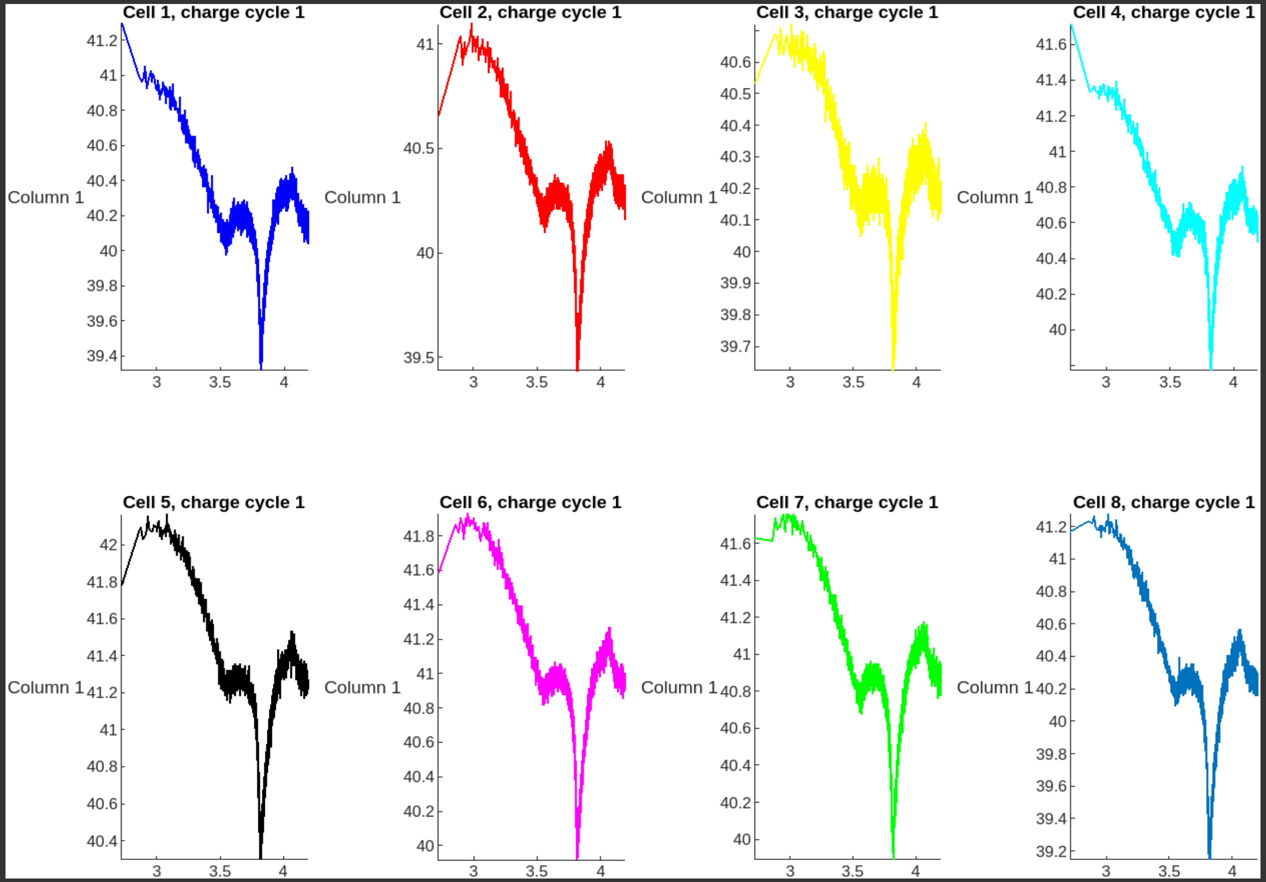
Experimental setup

- Open dataset: Oxford Battery Degradation, 8 Li-ion cells
- Voltage to temperature
- Data split: 80% training, 10% validation and 10% test
- MATLAB Deep Learning Toolbox



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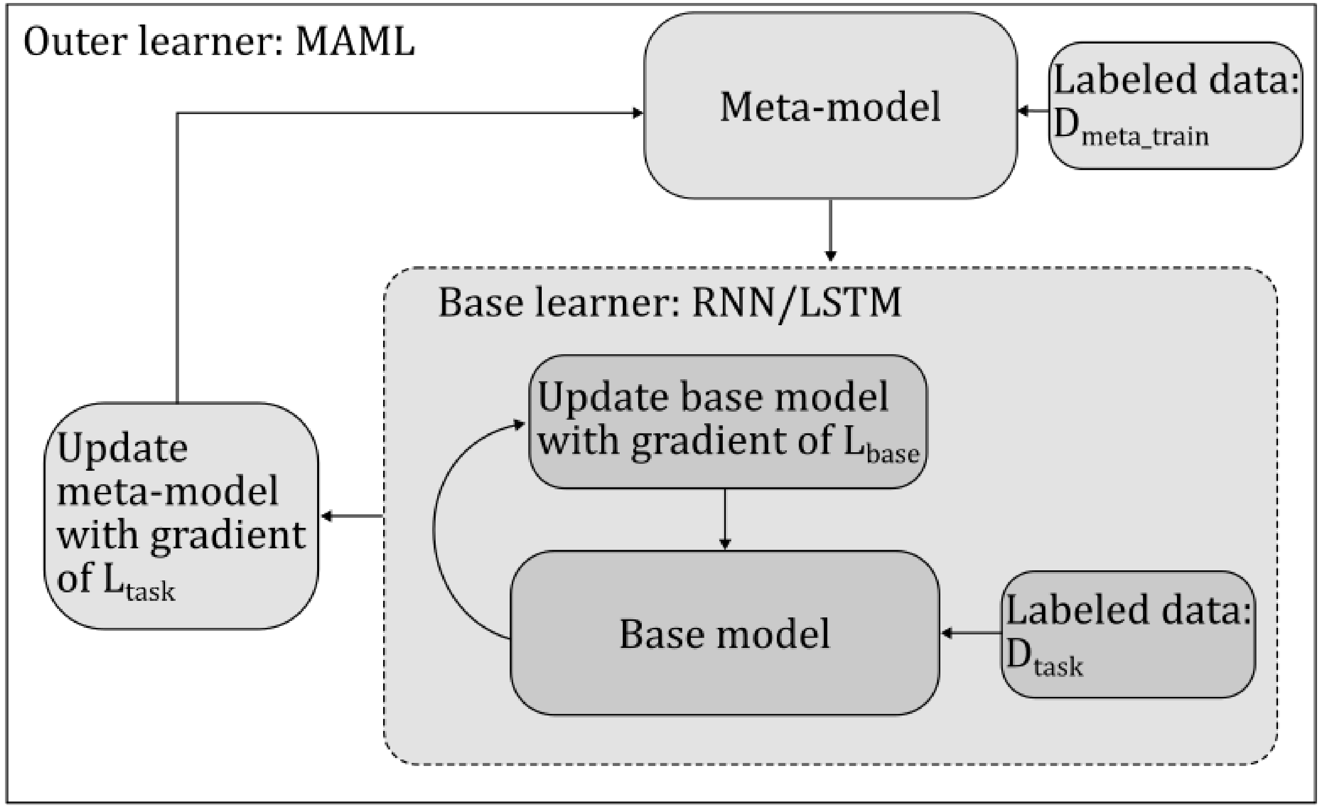
Training loop

Algorithm 1: Model-agnostic meta-learning
Require: $p(T)$: distribution over tasks
Require: α, β: step size hyper parameters
1: randomly initialize θ
2: while not done do
3: Sample batch of tasks $Ti \sim p(T)$
4: for all Ti do
5: Evaluate $\nabla\theta\ L\ Ti\ (f\theta)$ with respect to K examples
6: Compute adapted parameters with gradient descent : $\theta' i = \theta - \alpha\ \nabla\theta\ L\ Ti\ (f\theta)$
7: End for
8: Update $\theta \leftarrow \theta - \beta\ \nabla\theta\ \Sigma\ Ti \sim p(T)\ L\ Ti\ (f\theta')$
9: end while

Algorithm 2: Adaptation MAML
1: function ADAPT (f, Θ, Da; ϕ)
2: $\Theta0 \leftarrow \Theta$
3: for $j \in \{ 1 \ldots$ adaptation steps $\}$ do
4: $Lj \leftarrow L\ (Ya, f\ (Xa; \Theta\ j\text{-}1))$
5: $\Theta j \leftarrow \Theta\ j\text{-}1 - \phi\ \nabla\ \Theta\ j\text{-}1\ L\ j$
6: return Θ adaptation steps



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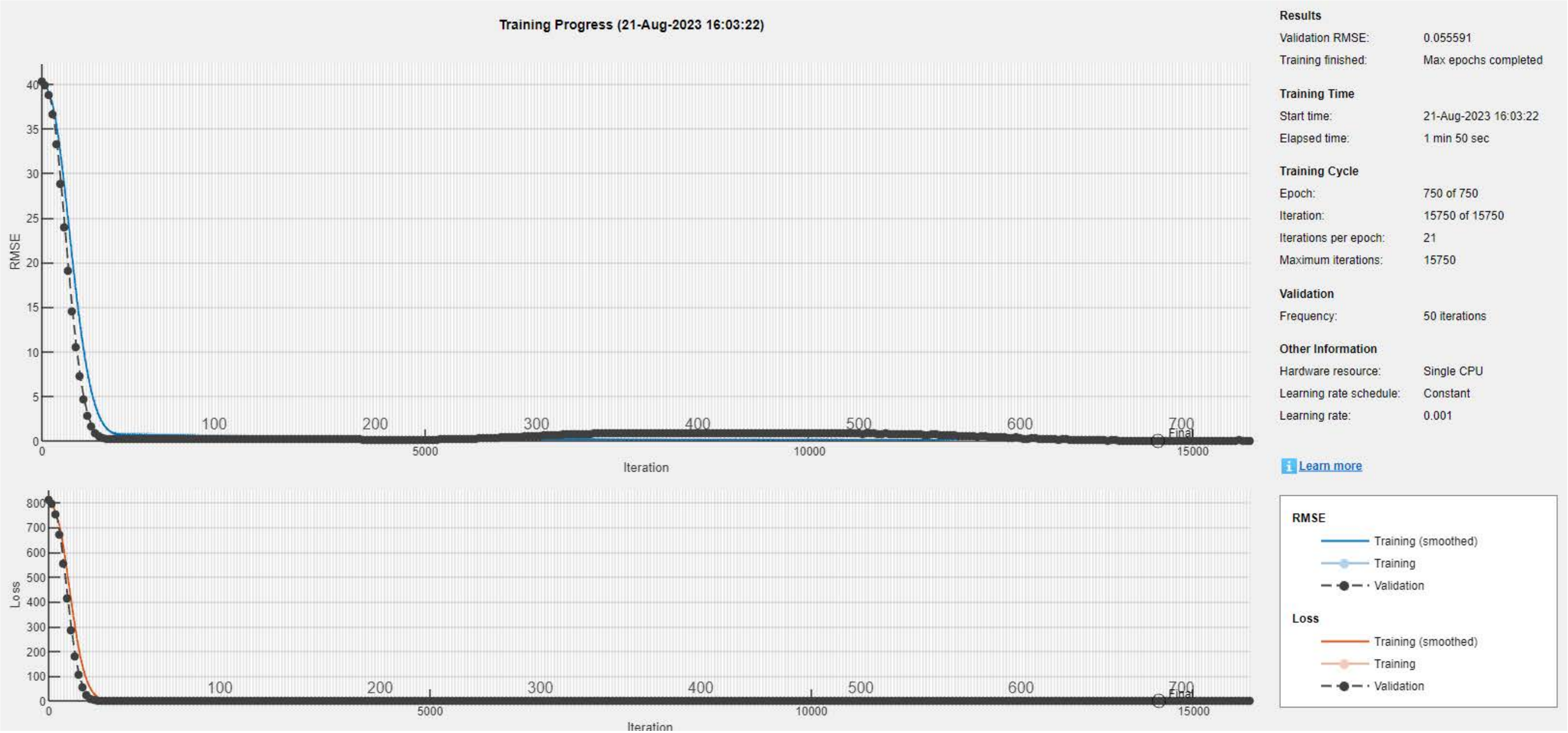
Intermediate results



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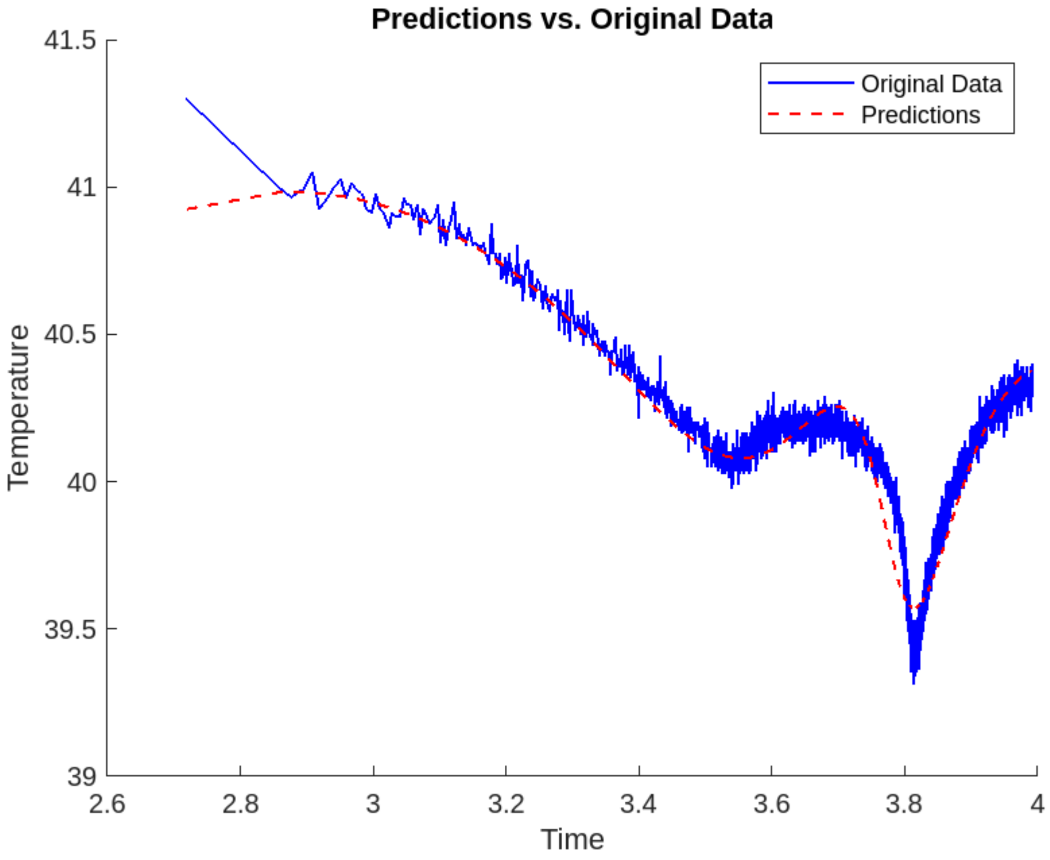

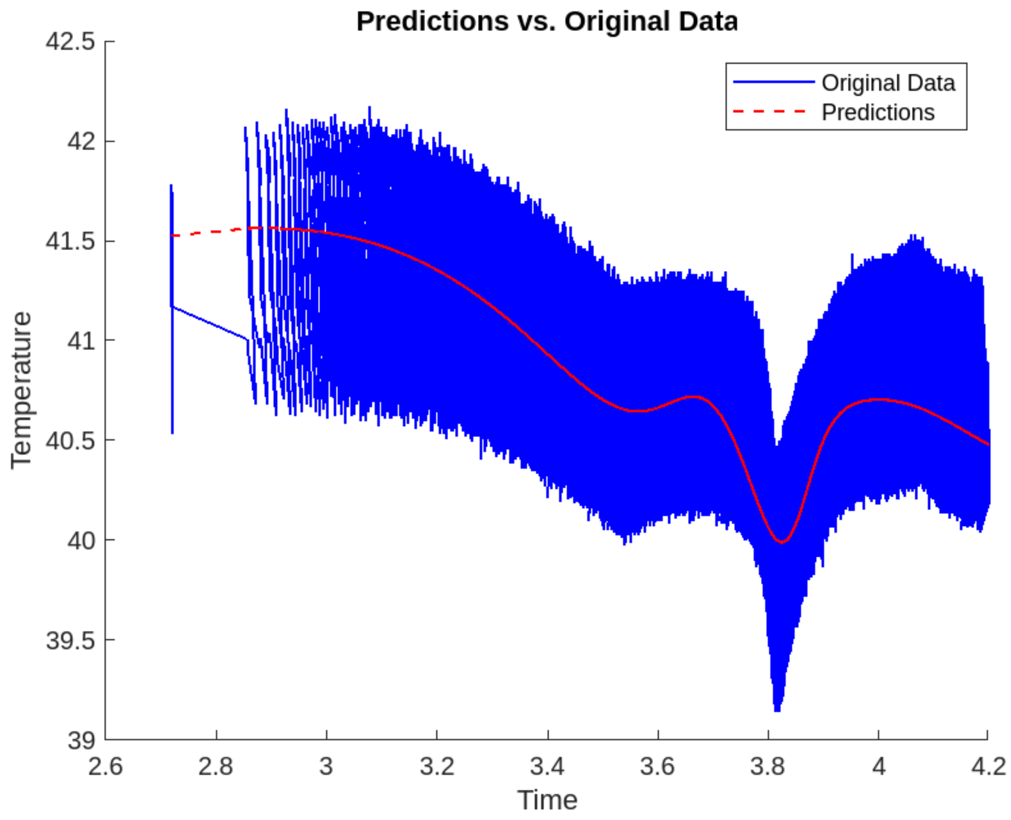

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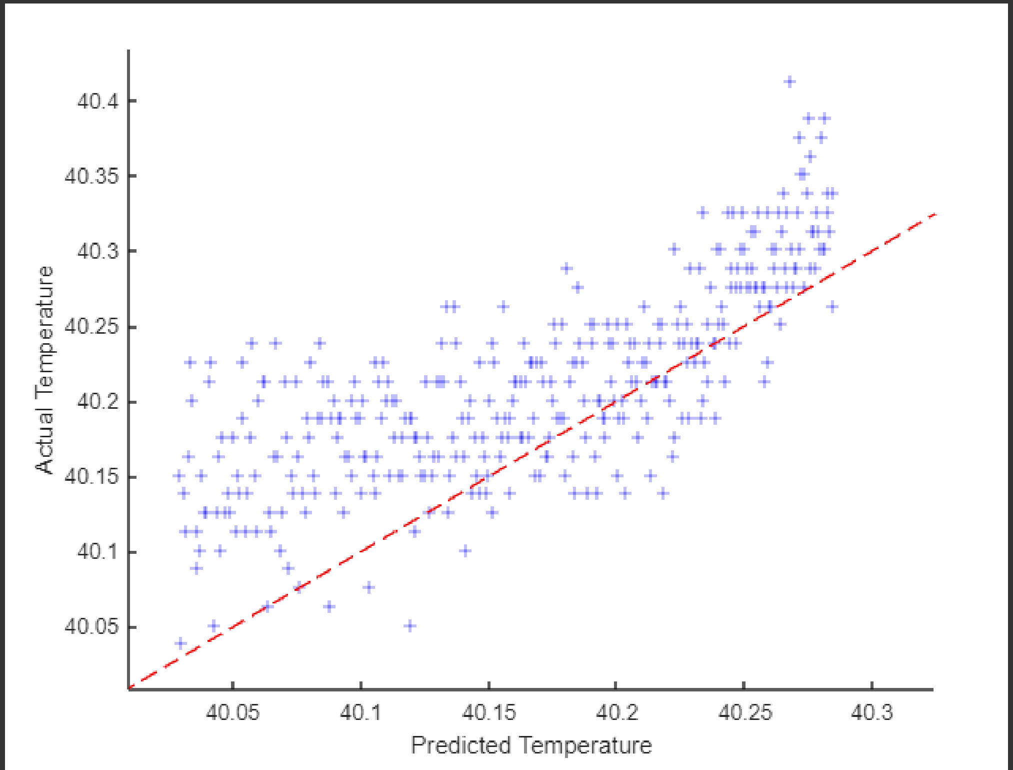
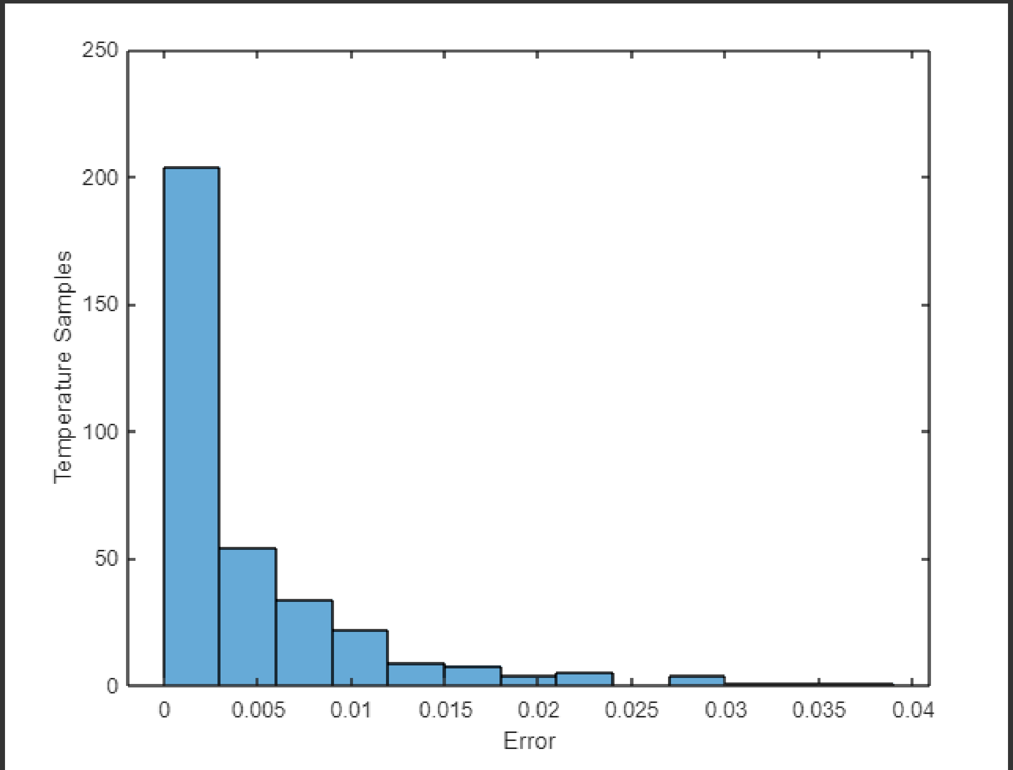
Prediction errors





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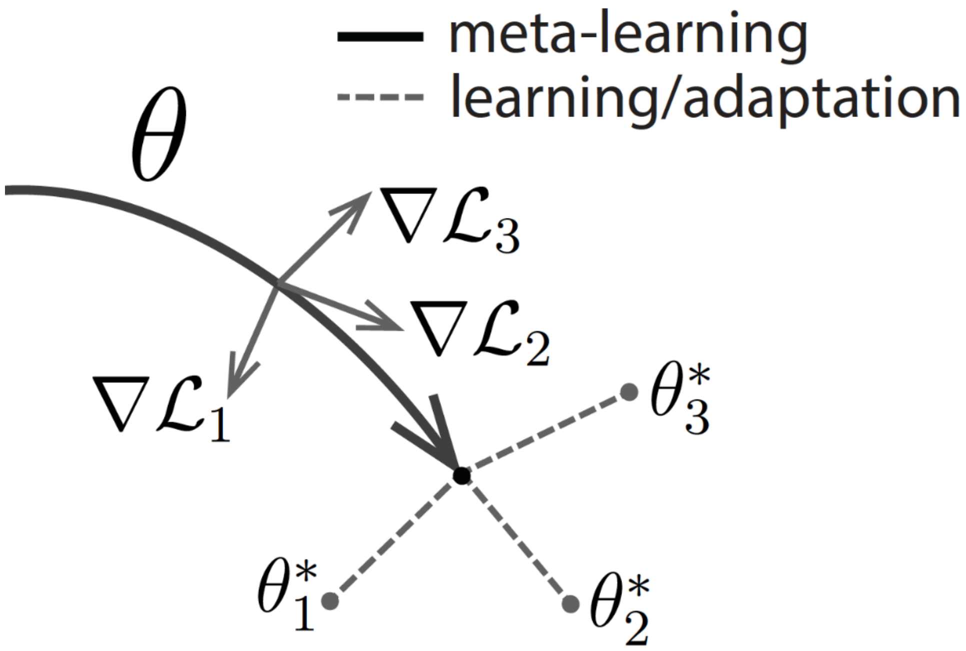

Conclusions & future work

Promising Outcomes:

- Enhanced Adaptation: MAML demonstrates remarkable adaptability to new tasks with minimal data.
- Generalization: Improved generalization abilities in a wide range of applications.

Future Research Directions:

- Fine-tuning Strategies: Investigate more efficient fine-tuning to boost model performance further
- Meta-Learner Architectures: Explore novel meta-learner architectures to enhance the learning process
- Robustness and Stability: Address issues related to robustness and stability when adapting to highly dynamic environments

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Thank you!