Friedrich-Alexander-Universität
Technische Fakultät

Chair for Computer Science 6 (Data Management)

Deep Transfer Learning Model Selection

In A Time Series Modeling Context

Melanie Bianca Sigl
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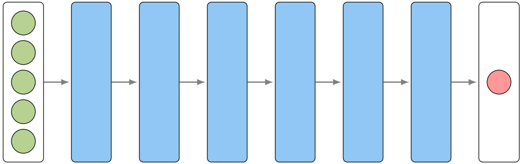
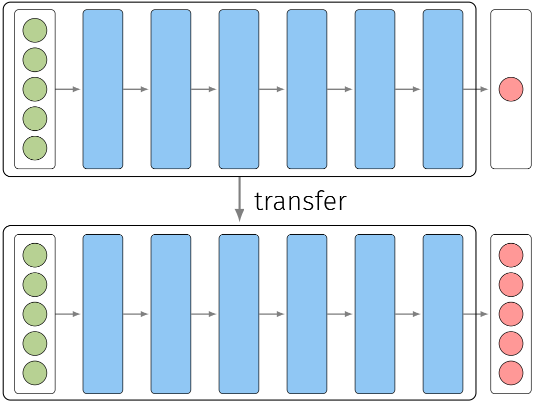
Deep Transfer Learning as State-of-the-Art

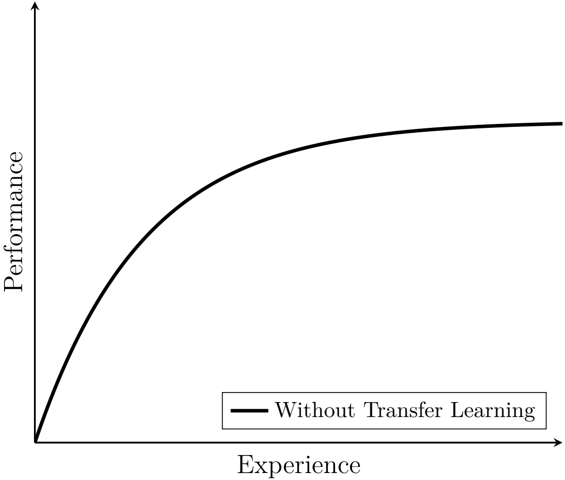


Deep Transfer Learning as State-of-the-Art

- **Reduce time to select a hyperparameter space**
- **Reduces training time**
- Reduces amount of models to train
- **Avoids overfitting**
- Even obtain **better results**



Three Signs Transfer Learning was Successful[1]



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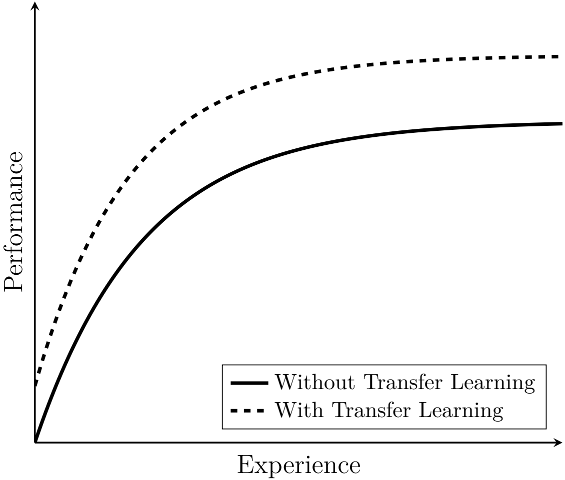

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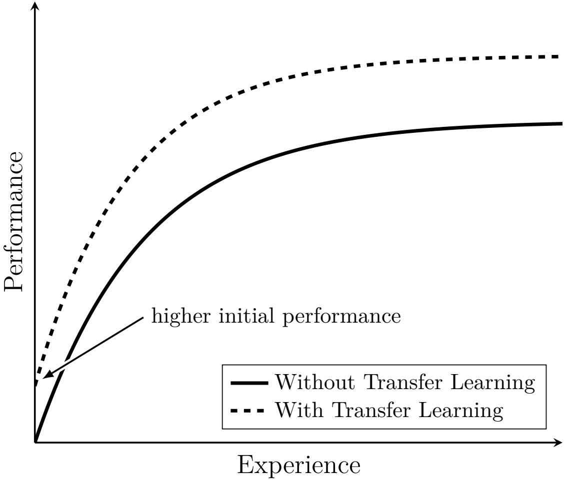

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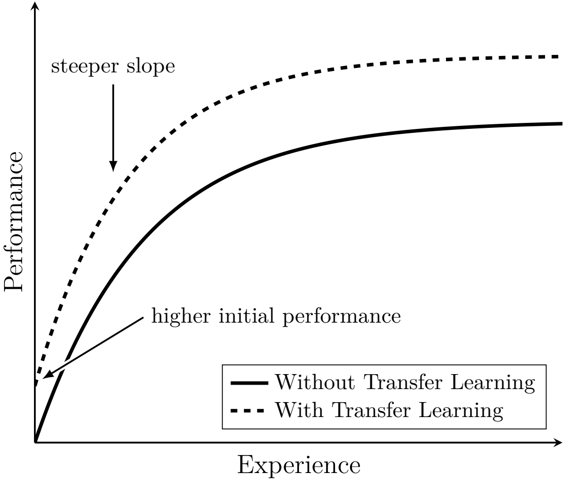

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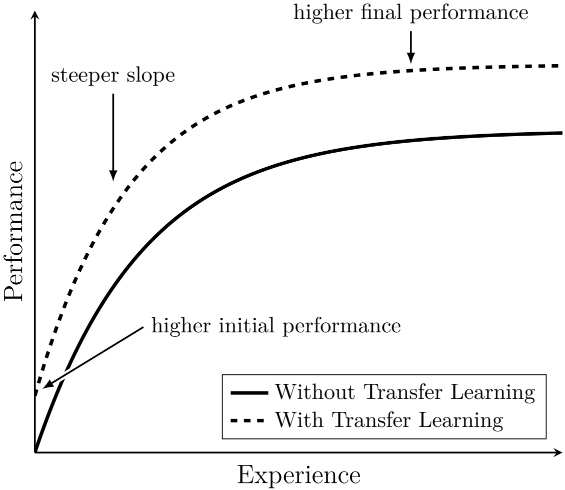

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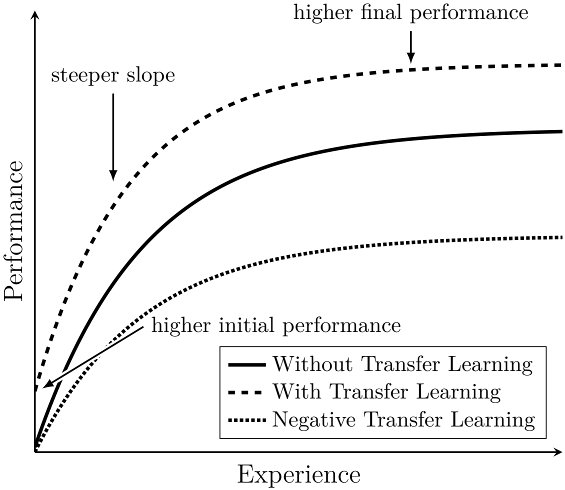

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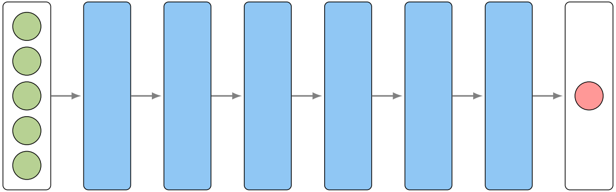
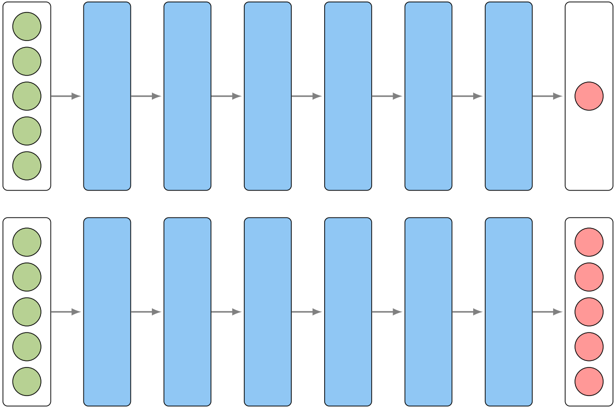
Possible Modifications of a Source DL Model: Which to Perform?

1. Base: Pre-trained DL Model



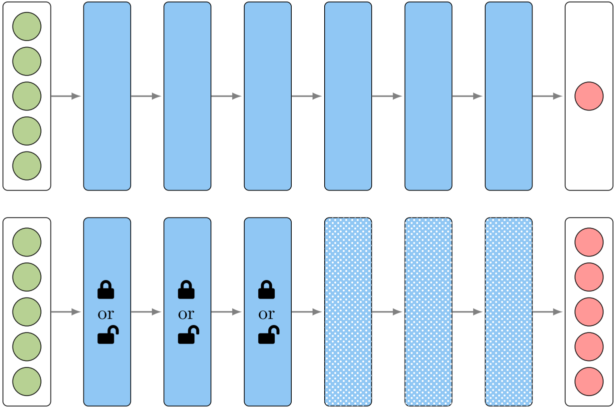
Possible Modifications of a Source DL Model: Which to Perform?

1. Base: Pre-trained DL Model
2. Change number of output neurons



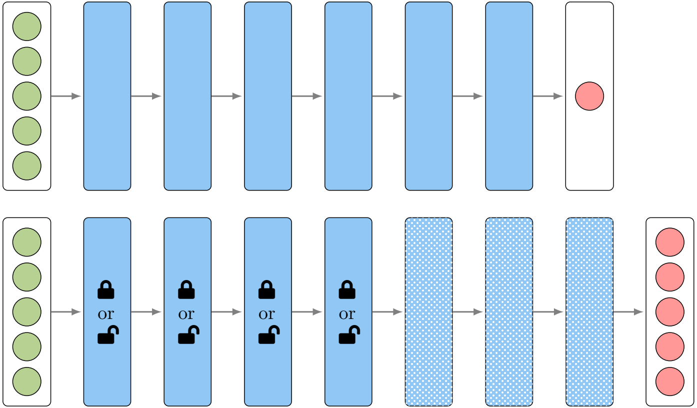
Possible Modifications of a Source DL Model: Which to Perform?

1. Base: Pre-trained DL Model
2. Change number of output neurons
3. Freeze first *n* hidden layers, fine-tune others or re-initialize weights



Possible Modifications of a Source DL Model: Which to Perform?

1. Base: Pre-trained DL Model
2. Change number of output neurons
3. Freeze first *n* hidden layers, fine-tune others or re-initialize weights
4. Add new hidden layer



Transferability is negatively affected by:

- Specialization of higher layer neurons $\rightarrow$ specialization towards target task[2]
- Increasing dataset and/or task dissimilarity[3]

Transfer learning is powerful:

- Initializing a network with transferred features results in a generalization boost that lingers after fine-tuning
- When target training dataset is significantly small
- Training of a large DL model without overfitting

[2] Jason Yosinski et al. "How transferable are features in deep neural networks?" In: *Advances in Neural Information Processing Systems 27*. Ed. by Z. Ghahramani et al. Curran Associates, Inc., 2014, pp. 3320–3328.

[3] Karl R. Weiss, Taghi M. Khoshgoftaar, and Dingding Wang. "A survey of transfer learning". In: *J. Big Data* 3 (2016), p. 9
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Abundance of Available DL Models: Which DL Model to Choose?

Numerous ”model repositories” exist, such as:

TensorFlow Hub Keras ONNX ModelDepot ModelZoo

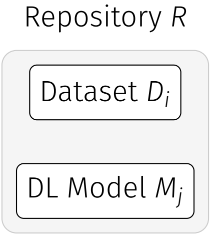
Problem:

An abundance of (freely) available pre-trained DL models complicates selection of an *appropriate* DL model for successful Transfer Learning.

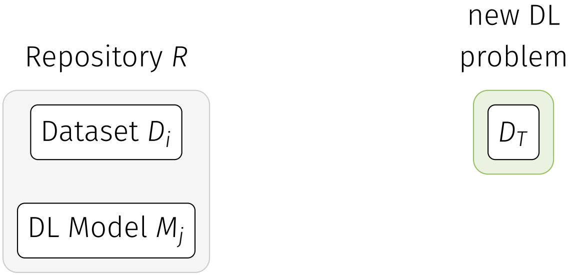
Design and build a **repository** to support the **search and selection** of one deep learning model for **transfer learning** such that, for a given new dataset and its task, the obtained model receives a **better performance measure** than training such a model from scratch.

> **Leading Hypothesis**
> If the training data of a stored model is similar to those of the new dataset, then this stored model is suitable for Transfer Learning.

Transfer Learning Framework



Transfer Learning Framework



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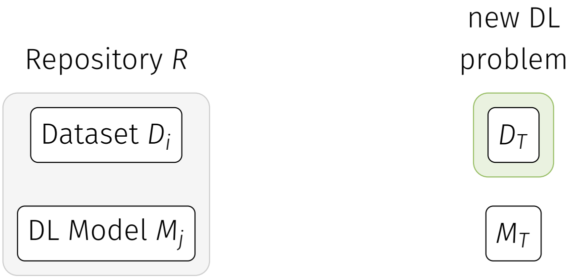

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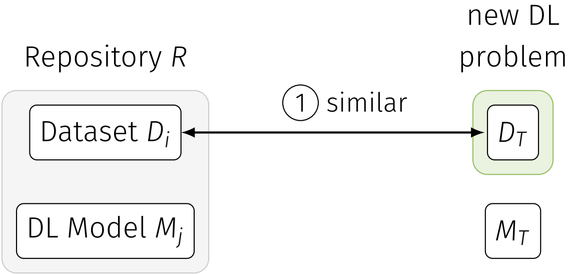

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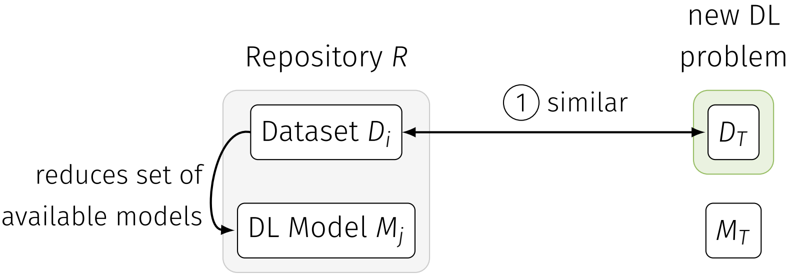

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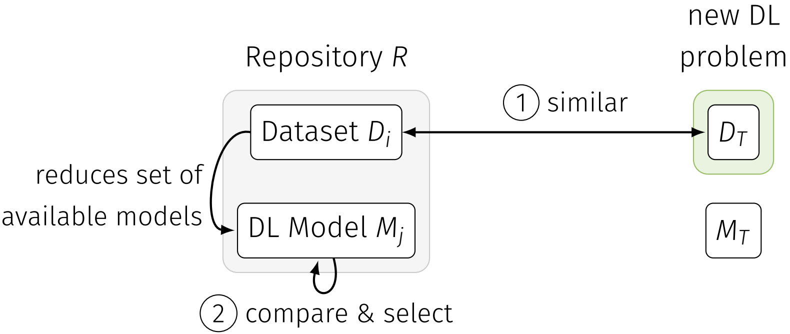

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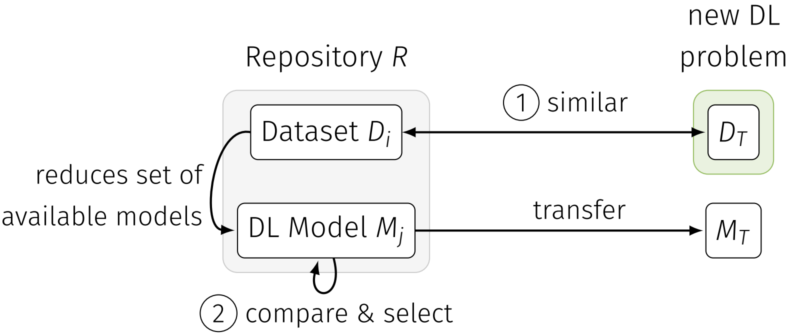

Transfer Learning Rarely Used in a Time Series Modeling Context

Transfer Learning for *Univariate* Time Series

- Ye and Dai [YD18]: Time series forecasting. Extract characteristics from univariate time series with extreme learning machine with kernels, train multiple models on these information, create ensemble models.[4]
- He, Pang, and Si [HPS19]: (Financial) time series forecasting. Train DL model on two source datasets.[5]
- Ye and Dai [YD21]: Time series forecasting. Find similar time series with DTW and Jensen-Shannon divergence, train CNN on similar time series and then fine-tune on both query and similar time series.[6]

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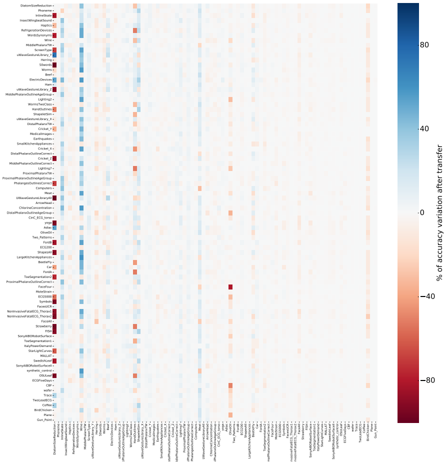
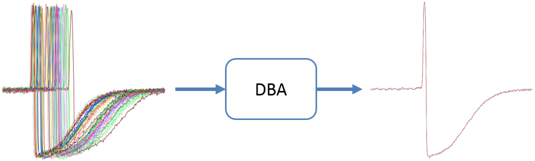
[4] Rui Ye and Qun Dai. "A novel transfer learning framework for time series forecasting". In: *Knowl. Based Syst.* 156 (2018), pp. 74–99.
[5] Qi-Qiao He, Patrick Cheong-Iao Pang, and Yain-Whar Si. "Transfer Learning for Financial Time Series Forecasting". In: *PRICAI 2019: Trends in Artificial Intelligence - 16th Pacific Rim International Conference on Artificial Intelligence, Cuvu, Yanuca Island, Fiji, August 26-30, 2019, Proceedings, Part II.* ed. by Abhaya C. Nayak and Alok Sharma. Vol. 11671. Lecture Notes in Computer Science. Springer, 2019, pp. 24–36.
[6] Rui Ye and Qun Dai. "Implementing transfer learning across different datasets for time series forecasting". In: *Pattern Recognit.* 109 (2021), p. 107617.

Fawaz et al.: Transfer Learning for Time Series Classification[7]





- 85 univariate time series + CNN
- Brute force Transfer Learning
- Replace output layer with new softmax layer and fine-tune
- 71/85 better with similarity
- Nearest neighbor not always best, sometimes 2nd nearest neighbor

[7] Hassan Ismail Fawaz et al. “Transfer learning for time series classification”. In: *IEEE International Conference on Big Data, Big Data 2018, Seattle, WA, USA, December 10-13, 2018*. Ed. by Naoki Abe et al. IEEE, 2018, pp. 1367–1376.

Searching Datasets for Transfer Learning

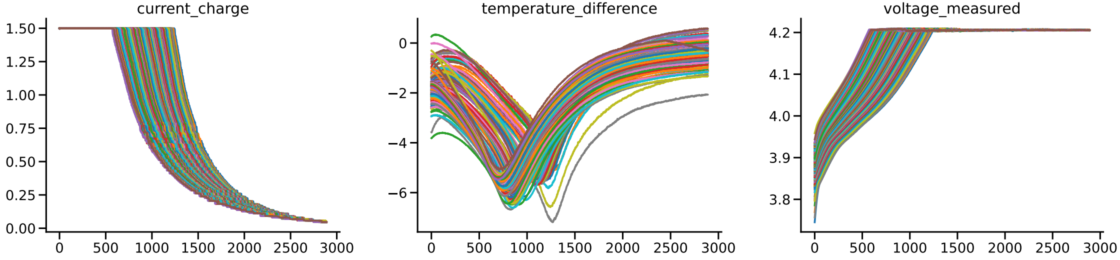
- Natural Language Processing (NLP) such as sentiment analysis, part-of-speech tagging, and named entity recognition. [RP17; Akd20; SLE18; LM20; Lin+19; Bä18]
  - [Lin+19]: Extract textual features such as type-token ratio, word overlap, phonological distance; train ensemble of decision-trees; select high-resource language for transfer learning for a low-resource language.
- Image datasets: [Bha+20; Sch+18; BEF19; Pra+19]
  - Compute dataset difficulty of dataset to search for datasets with similar difficulty [Sch+18; Ist+19]
  - [Pra+19]: Propose *dataset similarity ranker* for image datasets. Extract image related features, train several classifiers to predict which feature vector belongs to which dataset, enemble predictions.
- Extracted features depend on type of dataset (text vs. image). Various similarity functions used.

Data Set Characteristics for Similarity

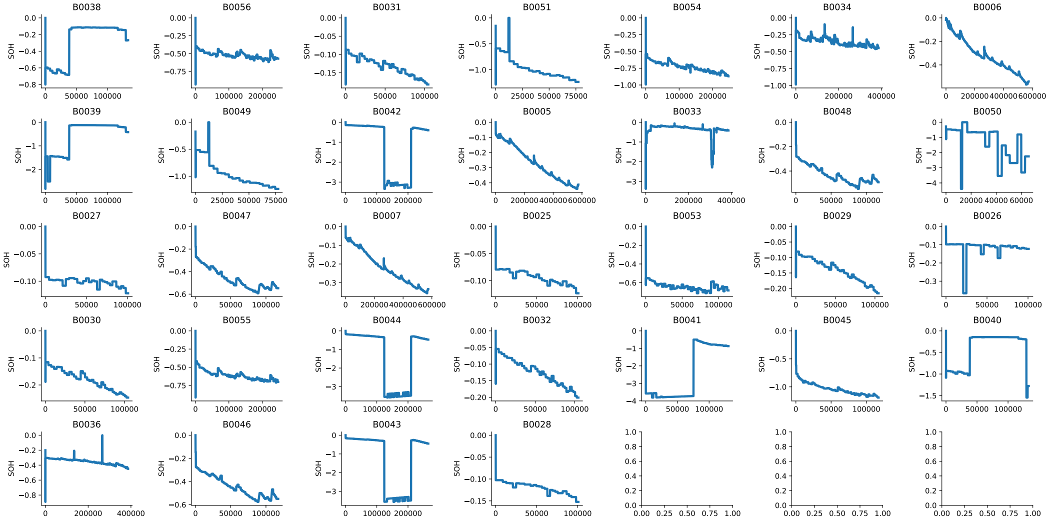
Dataset Used: NASA's Lithium Ion Battery Dataset

- NASA's Li-Ion battery dataset consisting of 34 data sets [SG07]
- In [Goe+08] the authors detail how they obtained the measurements of these batteries
- Battery EOL after losing 30% of its capacity.
- Datasets can be used for Predictive Maintenance and Remaining Useful Life (RUL) prediction.
- *State-of-Health* (SOH) is commonly used for RUL prediction. It states the current condition of a battery compared to its initial capacity. $\frac{\text{current capacity}}{\text{current capacity}}\%$

Dataset Used: NASA's Lithium Ion Battery Dataset



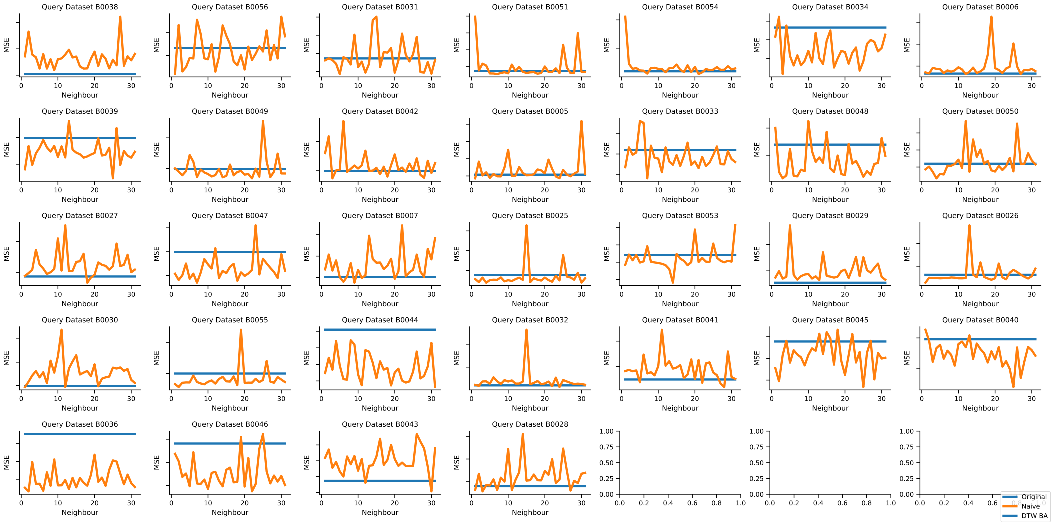
Lithium Ion Batteries State-of-Health of Each Battery



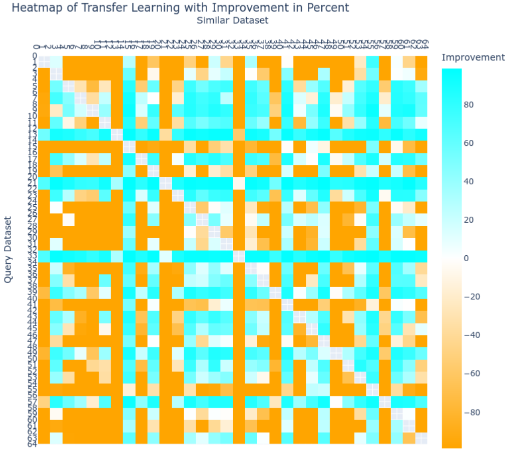
Naive Approach to Compute Time Series Similarity

- Descriptive statistics: minimum, maximum, mean, median, variance, standard deviation, quantiles (0.05, 0.25, 0.75, 0.95)
- Use Euclidean distance to order dataset.
- Perform brute force transfer learning where for each dataset the DL model of the first nearest neighbour is reused.
- Reuse: Re-initialize last layer (output layer) and retrain whole network.

Transfer Results Using Naive Dataset Similarity



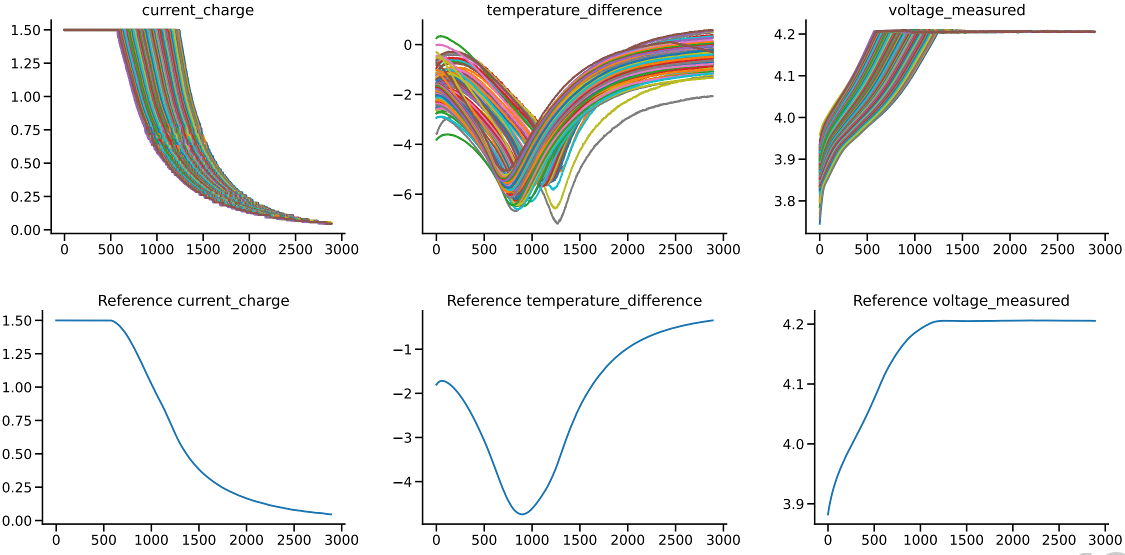
Currently Implemented Naive Time Series Similarity: Results



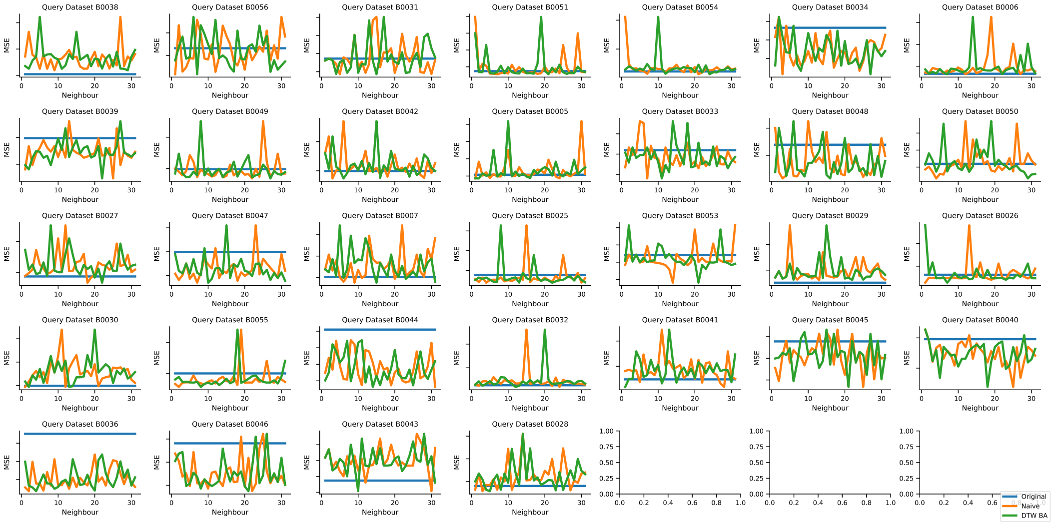
Summary

- Transfer learning shows positive improvement in some cases.
- Other cases show negative transferability.
- First nearest neighbour usually performs poorly.
- Second nearest neigbour also performs poorly.
- Distributional statistics not sufficient.

Create Reference Time Series Using DTW with Barycenter Averaging



Transfer Results: Naive Approach vs. DTW Barycenter Averaging



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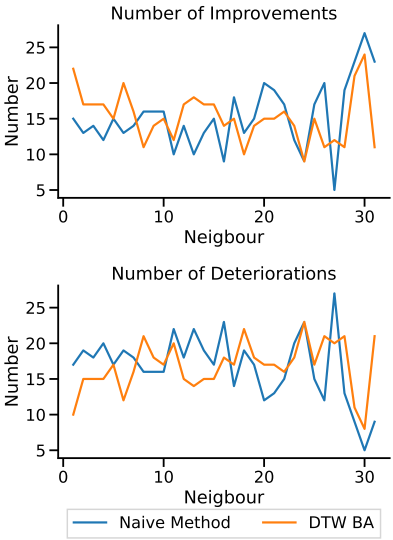

Summary

- DTW Barycenter Averaging generally performs better (first five neigbours)
- Interesting: Farthest neigbours of naive approach performs better
- Some datasets notoriously successful, whereas some always yield negative transfer results

Ways Forward to Improve Naive Similarity

- Extract **time-series specific characteristics** such as trend, seasonality, chaos, skewness, and kurtosis. Thus, extracting similar characteristics as Wang, Smith, and Hyndman [WSH06][8].
- **Extract further characteristics** as Fulcher and Jones [FJ14], albeit maybe not as much as they did (they extracted over 9,000 features).[9]

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[8] Xiaozhe Wang, Kate Smith, and Rob Hyndman. "Characteristic-Based Clustering for Time Series Data". In: *Data Mining and Knowledge Discovery* 13.3 (May 2006), pp. 335–364.

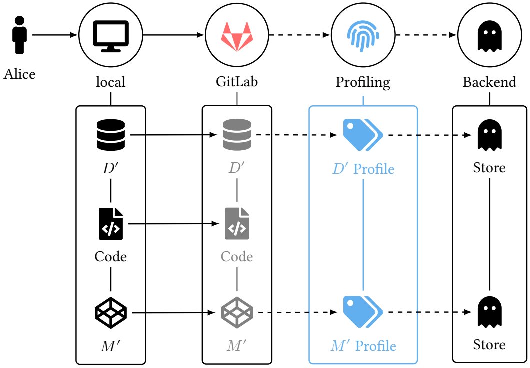
[9] Ben D Fulcher and Nick S Jones. "Highly comparative feature-based time-series classification". In: *IEEE Transactions on Knowledge and Data Engineering* 26.12 (2014), pp. 3026–3037.

Ways Forward to Improve DTW Barycenter Averaging Similarity

- Currently: Sum DTW distances of each dataset attribute.
- Find similar dataset similarity based on **individual attribute similarities**.
- DTW Barycenter Averaging method yields a reference time series that may not reflect the variability of a set of time series. Extend it with a **confidence interval**.

Data Structures for Transfer Learning

User Story and Architecture



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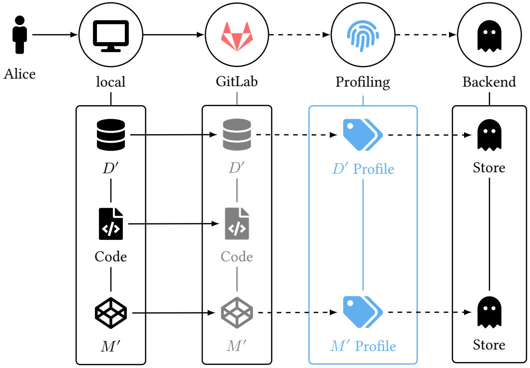

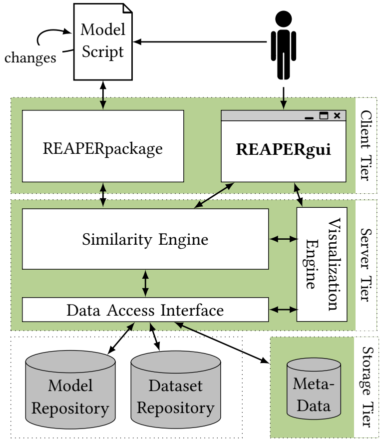

Summary and Ways Forward

Summary and Ways Forward

- Improve naive similarity approach by using dedicated time series characteristics
- Improve DTW Barycenter Averaging approach by extending to search for a similar attribute among all available attributes of another dataset; extend it by introducing a confidence interval.
- Use datasets from another domain such as NASA's turbofan engine degradation dataset
- Extend current regression task to time series classification

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[Bha+20] Bishwaranjan Bhattacharjee et al. “P2L: Predicting Transfer Learning for Images and Semantic Relations”. In: *2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition, CVPR Workshops 2020, Seattle, WA, USA, June 14-19, 2020*. IEEE, 2020, pp. 3284–3293.

[Bä18] Jesper Bäck. “Domain similarity metrics for predicting transfer learning performance”. PhD thesis. Linköping University, 2018.

[Faw+18] Hassan Ismail Fawaz et al. “Transfer learning for time series classification”. In: *IEEE International Conference on Big Data, Big Data 2018, Seattle, WA, USA, December 10-13, 2018*. Ed. by Naoki Abe et al. IEEE, 2018, pp. 1367–1376.

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