Deep Learning in the Frequency Domain: Advances, Challenges, and Applications for Time Series Analysis

Kun Yi[1], Qi Zhang[2], Wei Fan[3], Longbing Cao[4], Shoujin Wang[5], Hui He[6], Guodong Long[5], Liang Hu[2], Qingsong Wen[7], Hui Xiong[8]

[1]State Information Center, China [2]Tongji University, China [3]University of Oxford, UK [4]Macquarie University, Australia [5]University of Technology Sydney, Australia [6]Beijing Institute of Technology, China [7]Squirrel Ai Learning, USA [8]Hong Kong University of Science and Technology (Guangzhou), China

1 Intended Audience and Prerequisites

1.1 Intended Audience

This tutorial targets researchers, students, and practitioners interested in deep learning and time series analysis. The tutorial content is structured to cater to different levels of expertise:

- **Introductory Audience**: Basics of time series analysis, deep learning, and frequency domain methods.
- **Intermediate Audience**: Technical insights on integrating frequency analysis with neural networks and practical guidance on public code and datasets.
- **Advanced Audience**: Deeper exploration of practical applications, limitations, and future directions for frequency-domain enhanced deep learning models.

1.2 Prerequisite Knowledge

For this tutorial, no specific prerequisite knowledge or skills are required. However, basic knowledge of signal processing, machine learning, and deep learning concepts, particularly neural network architectures, and familiarity with fundamental time series analysis methods will benefit attendees.

2 Tutors

(1) *Dr. Kun Yi, Research Scientist* (Presenter & Contributor)
Affiliation: State Information Center
Postal Address: 58 Sanlihe Road, Beijing
Email: kunyi.cn@gmail.com
Homepage: https://github.com/aikunyi

(2) *Dr. Qi Zhang, Associate Professor* (Presenter & Contributor)
Affiliation: Tongji University
Postal Address: No. 1239 Siping Road, Shanghai
Email: zhangqi_cs@tongji.edu.cn
Homepage: https://sites.google.com/view/qizhang-bit-uts

(2) *Dr. Wei Fan, Postdoc Researcher* (Presenter & Contributor)
Affiliation: University of Oxford
Postal Address: 75 George Street, Oxford
Email: wei.fan@wrh.ox.ac.uk
Homepage: https://weifan.site

(3) *Dr. Qingsong Wen, Head of AI & Chief Scientist* (Presenter)
Affiliation: Squirrel Ai Learning
Postal Address: 800 Bellevue Way, Bellevue, Washington
Email: qingsongedu@gmail.com
Homepage: https://sites.google.com/site/qingsongwen8/

(4) *Dr. Hui Xiong, Chair Professor* (Corresponding tutor)
Affiliation: Hong Kong University of Science and Technology
Postal Address: 1 Duxue Road, Nansha District, Guangzhou
Email: xionghui@ust.uk
Homepage: https://www.hkust-gz.edu.cn/people/hui-xiong/

3 Tutors' Biography and Expertise

Kun Yi is affiliated with the State Information Center and specializes in deep learning with a focus on big data analytics and frequency-based methods for time series. His current research explores the integration of multimodal large language models (LLMs) into time series analysis to advance macroeconomic governance.

Qi Zhang is currently a associate professor at Tongji University. His research focuses on time series analysis, frequency-domain neural network, and general AI. Qi Zhang has published 60+ top-rank papers. He has also delivered 4 tutorials on data mining, recommender systems. Additionally, he has experience as a teaching assistant, teaching courses on Machine Learning and the Frontier of Computer Science at Tongji University.

Wei Fan is currently working as a Postdoctoral Researcher in the Medical Sciences Division at the University of Oxford, UK. His research focuses on data-centric AI, time series modeling, and spatial-temporal data mining. He is also dedicated to applying these methods to solve real-world data science applications, such as healthcare, transportation, and energy.

Qingsong Wen is currently the Head of AI & Chief Scientist at Squirrel Ai Learning. Before that, he worked at Alibaba, Qualcomm, Marvell, etc., and received his M.S. and Ph.D. degrees in Electrical and Computer Engineering from Georgia Institute of Technology, USA. His research interests include machine learning, data mining, and signal processing, especially AI for Time Series (AI4TS), LLM & AI Agent. Currently, he serves as Co-Chair of Workshop on AI for Time Series (AI4TS @ KDD, ICDM, SDM, AAAI, IJCAI). He also serves as Area Chair of NeurIPS, ICML, KDD, IJCAI, etc.

Hui Xiong is a Chair Professor at Hong Kong University of Science and Technology (Guangzhou) and Associate Vice President for Knowledge Transfer. He have had the privilege of contributing extensively to the fields of artificial intelligence, machine learning, and data science, and he is recognized as an IEEE Fellow, AAAS Fellow, AAAI Fellow and ACM Distinguished Scientist for his work in advancing knowledge in these domains. Before his time at the Hong Kong University of Science and Technology, he was a distinguished professor at Rutgers, the State University of New Jersey, from 2007 to 2021. His accolades include the AAAI-2021 Best Paper Award, the 2018 Ram Charan Management Practice Award, as the Grand Prix winner from the Harvard Business Review, the 2017 IEEE ICDM Outstanding Service Award, the 2016 RBS Dean's Research Professorship, the 2009 Rutgers University Board of Trustees

Research Fellowship for Scholarly Excellence, the ICDM-2011 Best Research Paper Award.

All tutors contributed to the preparation of the tutorial materials and will be attending KDD to present segments of the tutorial.

4 Brief Outline of Topics

- **Introduction and Motivation**
  - Overview of the growing importance of time series analysis
  - Key Issues and Challenges
  - Motivation for Frequency Domain Analysis
- **Foundations of Frequency Transformation**
  - Review of Discrete Fourier Transform (DFT), Discrete Cosine Transform (DCT), etc
  - Theoretical Foundations of Frequency-Domain Methods in Time Series Analysis
- **Deep Learning Approaches in the Frequency Domain**
  - Feature Engineering Approaches: Seasonal/periodic feature extraction, multi-scale wavelet coefficients
  - Compression and Noise Filtering: Leveraging low-frequency components to remove high-frequency noise
  - Fourier Neural Operators: Introduction to neural operator theory and efficient architectures (e.g., PDE-based modeling)
- **Applications across Time Series Tasks**
  - Time Series Forecasting
  - Anomaly Detection and Imputation
  - Time Series Classification
- **Advantages and Limitations**
  - Loss of fine-grained temporal detail and phase information
  - Complexity of multi-resolution feature fusion
  - Integrating time-frequency transforms for both local and global patterns
- **Challenges and Future Directions**
  - Novel Orthogonal Transform Methods (Partial Fourier, Fractional Fourier, orthogonal polynomial expansions)
  - Joint Learning in Time and Frequency: Hybrid frameworks combining time-domain and frequency-domain encoders
  - Scaling Up: Handling high-dimensional, large-scale time series using multi-GPU or distributed processing

5 Related Previous Tutorials

The proposed tutorial is related to the following tutorials presented in previous conferences. However, with the recent surge of interest in frequency-domain approaches for enhancing deep learning models in time series analysis, there is no formal tutorial comprehensively reviewing the interplay between deep learning and frequency analysis in the time series setting.

- *Qingsong Wen, Yuxuan Liang, Dongjin Song, Shirui Pan, Ming Jin. Foundation Models for Time Series Analysis: A Tutorial and Survey. In AAAI 2025.*
  https://aaai.org/conference/aaai/aaai-25/tutorial-and-lab-list
  This is a tutorial that offers insights into foundation model theory, implementation, and practical applications, including principles, pre-processing techniques, and modeling strategies. Differently, our proposed tutorial for KDD 2025 is focusing on the nature of time series in the frequency domain and innovatively reviewing the techniques of the frequency-domain signal processing.
- *Qingsong Wen, Yuxuan Liang, Dongjin Song, Shirui Pan. Foundation Models for Time Series Analysis: A Tutorial and Survey. In SIGKDD 2024.*
  https://wenhaomin.github.io/FM4TS.github.io/
  This is a tutorial that presents the research on foundation models of time series analysis including model architectures, pretraining techniques, adaptation methods, and data modalities. Our proposed tutorial for KDD 2025 is more focusing how deep learning models is combined with frequency analysis and transformation methods to benefit for time series modeling.
- *Qingsong Wen, Linxiao Yang, Tian Zhou, Liang Sun, Robust Time Series Analysis and Applications: An Industrial Perspective. In SIGKDD 2022.*
  https://qingsongedu.github.io/timeseries-tutorial-kdd-2022/
  This is a comprehensive and organized tutorial on the state-of-the-art algorithms of robust time series analysis, ranging from traditional statistical methods to the most recent deep learning based methods. There are some shared frequency-domain techniques introduced in this tutorial for the robust time series analysis. However, our proposed KDD 2025 tutorial focus on the general techniques involving frequency analysis and deep learning, targeting for more accurate, generalizable, reliable time series modeling, instead of only focusing robust time series.

6 Audience Engagement Strategies

To foster audience participation and interactivity throughout the tutorial presentation, we plan to employ the following strategies:

- Interactive Slides: We will design the slides to be visually engaging and interactive, incorporating elements such as clickable links, animated graphics, and embedded quizzes or polls. This will encourage attendees to actively engage with the content.
- Live Demonstrations: We will supplement theoretical discussions with live demonstrations of practical implementations and case studies. By showcasing real-world applications of the concepts being discussed, attendees will have the opportunity to see how the theoretical knowledge translates into practical solutions.
- Q&A Sessions: We will allocate dedicated time for Q&A sessions after each major topic or section covered in the tutorial. This will allow attendees to seek clarification on any concepts they find challenging and engage in direct dialogue with the presenters.
- Use of Supporting Materials: We will leverage the supporting materials provided, such as slides, audio/video recordings, and detailed references, to enrich the learning experience and encourage attendees to explore additional resources.
- Encouraging Questions and Contributions: Throughout the presentation, we will actively encourage attendees to ask questions, share their experiences, and contribute to discussions. Creating a supportive and inclusive atmosphere will empower attendees to actively participate and engage with the content.

7 Societal Impacts

This tutorial holds significant societal implications by enabling enhanced decision-making and predictive capabilities in critical areas including finance, healthcare, environmental monitoring, and IoT systems. The integration of frequency transformation with deep learning enhances interpretability, scalability, efficiency, and privacy-preserving capabilities, significantly benefiting practical, data-driven decision-making processes and innovation.