MEEG 491V/591V Machine Learning for Mechanical Engineers

Fall 2021
Mon/Wed/Fri 10:45 – 11:35 AM, BELL 2284

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Lecture Hours and Location: Mon/Wed/Fri 10:45 AM – 11:35 AM at BELL 2284

Office Hours and Location: Mon/Wed 2 – 3 PM at MEEG 106

Prerequisite: MEEG 2703 and MEEG 3503

Corequisite: MEEG 4103

Software Packages: Python, TensorFlow, Keras, Numpy, Jupyter Notebook, MATLAB.

Course Description: This course covers an introduction to selected supervised learning, unsupervised learning, and reinforcement learning algorithms for applications in mechanical engineering, including visualization-based physical quantity predictions, dynamic signal classification, and prediction, data-driven control of dynamical systems, surrogate modeling, dimensionality reduction, among others. The lectures cover the fundamental concepts and examples of developing machine learning models using Python and MATLAB. This course includes eight homework assignments to practice the application of different machine learning algorithms in specific mechanical engineering problems. It also includes a project assignment that gives the students the flexibility of selecting their topics to study using designated machine learning tools.

Learning Outcomes: Students completing this course are expected to be capable of

- Develop machine learning models using Python/TensorFlow and MATLAB
- Develop emulators or surrogate models for computationally expensive numerical simulations
- Develop machine learning models for anomaly detection and prediction of dynamic signals
- Analyze images/maps from experiments and simulations to predict physical quantities
- Adapt trained machine learning models to new applications
- Design data-driven control models
- Extract features and patterns from data and discover new knowledge
- Examine the reliability and robustness of data-driven models

Face Mask Requirement: Per university policy, face masks are currently required. Face masks need to be worn properly (CDC's guidance: [Your Guide to Masks | CDC]).

Lecture Topics:

Topic 1: Introduction to Artificial Intelligence, Machine Learning, and Data-Driven Modeling

- Learning objectives*:* understand the definition of artificial intelligence, machine learning, and data-driven modeling and their relationships with experiments and physics-based models; get familiar with software and hardware for machine learning programming.

- Content:
  - What is machine learning, why is it needed for mechanical engineers
  - Supervised learning, unsupervised learning, and reinforcement learning
  - Data-driven models vs physics-based models
  - How to set up machine learning models; how to use machine learning libraries
  - How to set up machine learning tests on CPU/GPU clusters
- Practice:
  - Install Anaconda, Python, TensorFlow, Keras
  - Set up machine learning tests on CPU/GPU clusters
  - Reading: Keras (Code examples (keras.io)); Python tutorial (A Whirlwind Tour of Python);
  - Short-essay writing (2-page): Describe any problems you have in mind to solve using machine learning, any machine learning approaches you are particularly interested in, and your plan of using machine learning in your research or other courses.

Topic 2: Visualization-Based Physical Quantity Predictions

- Learning objectives: Understand the algorithms of classification and regression of images and image sequences; develop, train, and test neural networks for image analysis; interpret the predictions of the neural networks.
- Content:
  - Convolutional neural networks (CNN)
  - Training curves and overfitting
  - Image classification of 1D/2D/3D images
  - Image regression
  - Generative adversarial networks (GAN)
  - Interpretability and activation visualization
- Practice:
  - Develop a CNN model to predict the quantity. Students can select their topics and datasets or use provided datasets (MNIST, boiling images, etc.).

Topic 3: Dimensionality Reduction and Transforms

- Learning objectives: understand the working principles of dimensionality reduction and transformers and apply them to solve engineering problems.
- Content:
  - Principal component analysis (PCA)
  - Robust principal component analysis (RPCA)
  - Discrete Fourier transform (DFT) and fast Fourier transform (FFT)
- Practice:
  - Perform PCA for provided data sets and examine the variance different principal components cover.
  - Perform PCA and RPCA for provided data/image sets and compare their performance.
  - Perform FFT for provided data sets to remove the noise of the data.

Topic 4: Dynamic Signal Analysis: Anomaly Detection and Data Forecasting

- Learning objectives: Learn the techniques of identifying patterns in dynamic signals, detecting anomalies in dynamic signals, and forecasting the near-future signals.

- Content:
  - Sequence classification and sequence prediction
  - Recurrent neural networks (RNN) and long short-term memory (LSTM)
  - Convolutional long short-term memory (LSTM) for higher-dimensional data
- Practice:
  - Develop LSTM networks for sequence prediction.
  - Develop CNN and LSTM networks for sequence classification.

Topic 5: Emulation and Surrogate Modeling for Physics-Based Models

- Learning objectives: Develop emulators or surrogate models for numerical simulations; evaluate the tradeoff of the computational cost and fidelity of the emulators.
- Content:
  - Subset selection for regression
  - Multi-agent reinforcement learning
  - Gaussian process regression
  - Fidelity vs. computational cost
- Practice:
  - Develop a multi-fidelity learning model using Gaussian process regression and reinforcement learning.
  - Train and test the model on data from computational fluid dynamics simulations.

Topic 6: Model Adaptation for New Datasets and New Applications

- Learning objectives: Understand the algorithms of adapting trained models to new datasets and new applications; implement transfer learning in CNN and reinforcement learning models.
- Content:
  - Introduction to Transfer learning (TL)
  - Instance, feature, model-based transfer learning
  - Transfer learning with reinforcement learning
  - Transfer learning in computer vision
- Practice:
  - Adapt the CNN model developed in Project 1 to a new dataset using transfer learning.
  - Test the accuracy of the TL model for varying model architecture and percentage of training data.

Topic 7: Data-Driven Control of Dynamic Systems

- Learning objectives: develop data-driven models using reinforcement learning and genetic algorithms to enable automatic control of dynamic systems.
- Content:
  - Dynamic mode decomposition
  - Linear control theory
  - Reinforcement learning (RL)
  - Genetic algorithms (GA)
- Practice:
  - Design a control algorithm to enable active control of provided dynamical systems.

Topic 8: Feature Extraction and Selection in Data Mining

- Learning objectives: Understand the algorithms for extracting the features of a dataset and choosing a subset of the original pool of features
- Content:
    - Feature extraction and selection
    - *k*-means clustering and hierarchical clustering
    - PCA and clustering
    - Supported vector machines
    - Regression
- Practice:
    - Identify the key patterns of properties of ordered and disordered materials.

Topic 9: Artificial Intelligence for Design Optimization

- Learning objectives: study algorithms for design optimization in parametric studies as well as in CAD of mechanical parts.
- Content:
    - Genetic algorithm-based parameter optimization
    - Generative design and topology optimization
- Practice:
    - Propose an AI-based design problem. Possible topics include integrated GA and molecular dynamics; integrated GA and computational fluid dynamics; CAD with generative design.

Communication: In this class, our official mode of communication is through uark.edu email and Blackboard. Students are responsible for checking their UARK accounts regularly. All communication between student and instructor and between student and student should be respectful and professional.

Grading Policy:

Homework	40%	40 points
Supercomputing	10%	10 points
Project	50%	50 points
Total	100%	100 Points

Grading Scale: 90's = A, 80's = B, 70's = C, 60's = D, Below 60's = F

Project: Students will leverage machine learning to solve an engineering problem. Students will be provided with a few topics and can select a topic from the provided options. On the other hand, students are encouraged to think out of box and define the topic of their projects based on their research needs and interest. The following documents will need to be submitted for the project.

- Abstract (5%): Students will need to prepare a 300-word abstract to describe the topic they want to study. The instructor will evaluate the relevance and feasibility of the proposed topic.

- Proposal (10%): After the selected topic is approved, students will prepare a three-page proposal to detail the background, approach, and plan for the proposed study.

- Quad Chart & Presentation (5%): By the end of the semester, students will prepare a quad chart one-slider using the provided template to summarize their work and do a one-minute elevator pitch.
- Final Report (30%): Besides the presentation, students will also need to prepare a final report for their projects. The source codes and instructions to run the source codes should be submitted with the final report.

Code Performance and Scaling on Supercomputers (Supercomputing): Graduate students enrolled in MEEG 591V are required to benchmark the scaling performance of their machine learning models on CPUs and GPUs using Bridges RM, Bridges GPU, and Bridges GPU AI via XSEDE allocations. The code performance benchmark on supercomputers accounts for 10% of total credits.

The supercomputing assignment is optional for undergraduate students enrolled in MEEG 491V. If they opt out, their grades of the supercomputing assignment will be the same as their homework assignments.

Homework and Project Evaluation Criteria: Students need to submit a written report for each homework assignment and each project along with their codes. The development of the machine learning models accounts for 40% of the credits, the successful implementation accounts for 30%, and the presentation/report accounts for the other 30%.

Late Homework and Project Submission: Students can request deadline extensions for homework assignments and projects in case of special circumstances including family emergency, sickness, *etc*. Deadline extensions will only be offered when the student notifies the instructor ahead of time with an explanation and plan for completion. Late homework assignments and projects without prior arrangements can only account for up to 50% of the full credits.

Student Accommodations: University of Arkansas *Academic Policy Series 1520.10* requires that students with disabilities are provided reasonable accommodations to ensure their equal access to course content. If you have a documented disability and require accommodations, please contact me privately to make arrangements for necessary classroom adjustments. Please note, you must first verify your eligibility for these through the Center for Educational Access (contact ada@uark.edu or visit *http://cea.uark.edu* for more information on registration procedures).

Academic Honesty: As a core part of its mission, the University of Arkansas provides students with the opportunity to further their educational goals through programs of study and research in an environment that promotes freedom of inquiry and academic responsibility. Accomplishing this mission is only possible when intellectual honesty and individual integrity prevail. Each University of Arkansas student is required to be familiar with and abide by the University's 'Academic Integrity Policy' which may be found at http://provost.uark.edu/. Students with questions about how these policies apply to a particular course or assignment should immediately contact Dr. Hu.

Students are not permitted to collaborate on any quiz or examination without specific permission from the instructor in advance. This includes collaboration through GroupMe, WhatsApp, or any other form of technology to exchange information associated with a quiz or examination.

The following is not all inclusive of what is considered academic misconduct for quizzes or examinations. These examples show how the use of technology can be considered academic misconduct and could result in the same penalties as cheating in a face-to-face (in person) class:

- Taking a screen shot of an online quiz or exam question, posting it to GroupMe or WhatsApp, and asking for assistance is considered academic misconduct.
- Answering an online quiz or exam question posted to GroupMe or WhatsApp is considered academic misconduct.
- Giving advice, assistance, or suggestions on how to complete a question associated with a quiz or examination is considered academic misconduct.
- The use of online websites (Quizlet, Chegg) or search engines (Google) when exam instructions indicate these are not allowed is considered academic misconduct.
- Gathering to take an online quiz or exam with others and sharing answers in the process is considered academic misconduct.

Please note: If a student or group of students are found to be exchanging material associated with a quiz or examination through any form of technology (GroupMe, WhatsApp, *etc.*) or using any unauthorized resources (Googling answers, use of websites such as Quizlet, Course Hero, Chegg, etc.), I am required to report this matter per the University of Arkansas Academic Integrity Policy.

There are many websites claiming to offer study aids to students, but in using such websites, students could find themselves in violation of our University's Academic Integrity and Code of Student Life policies. These websites include (but are not limited to) Quizlet, Bartleby, Course Hero, Chegg, and Clutch Prep. The U of A does not endorse the use of these products in an unethical manner. These websites may encourage students to upload course materials, such as test questions, individual assignments, and examples of graded material. Such materials are the intellectual property of instructors, the university, or publishers and may not be distributed without prior authorization. Furthermore, paying for academic work to be completed on your behalf and submitting it for academic credit is considered 'contract cheating' per the Academic Integrity Policy. Students found responsible for this type of violation face a grading penalty of 'XF' and a minimum one-semester academic suspension per the *University of Arkansas Sanction Rubric*. Please let me know if you are uncertain about the use of a website.

Unauthorized Use of Class Recordings ante Notes: Instructors may record class and make class available to students through Blackboard. These recordings may be used by students ONLY for the purposes of the class. Students may not download, store, copy, alter, post, share, or distribute in any manner all or any portion of the class recording, e.g. a 5-second clip of a class recording sent as a private message to one person is a violation of this provision. This provision may protect the following interests (as well as other interests not listed): faculty and university copyright; FERPA rights; and other privacy interests protected under state and/or federal law. Failure to comply with this provision will result in a referral to the *Office of Student Standards and Conduct* for potential charges under the *Code of Student Life*. In situations where the recordings are used to gain an academic advantage, it may also be considered a violation of the *University of Arkansas' academic integrity policy*.

Recording, or transmission of a recording, of all or any portion of a class is prohibited unless the recording is necessary for educational accommodation as expressly authorized and documented through the *Center for Educational Access* with proper advance notice to the instructor. Unauthorized recordings may violate federal law, state law, and university policies. Student-made recordings are subject to the same restrictions as instructor-made recordings. Failure to comply with this provision will result in a referral to the *Office of Student Standards and Conduct* for potential charges under the *Code of Student Life*. In situations where the recordings are used to gain an academic advantage, it may also be considered a violation of the *University of Arkansas' academic integrity policy*.

By attending this class, student understands the course is being recorded and consents to being recorded for official university educational purposes. Be aware that incidental recording may also occur before and after official class times.

Third parties may attempt to connect with you to buy your notes and other course information from this class. I will consider distributing course materials to a third party without my authorization a violation of my intellectual property rights and/or copyright law as well as a violation of the *University of Arkansas' academic integrity policy*. Continued enrollment in this class signifies your intent to abide by the policy. Any violation will be reported to the *Office of Academic Initiatives and Integrity*.

Please be aware that such class materials that may have already been given to such third parties may contain errors, which could affect your performance or grade. Recommendations for success in this course include coming to class on a routine basis, visiting me during my office hours, connecting with the Teaching Assistant (TA), and making use of Student Success Center. If a third party should contact you regarding such an offer, I would appreciate your bringing this to my attention. We all play a part in creating a course climate of integrity.