Engineering Tripos Part IIB, 4C11: Data-driven and learning based methods in mechanics and materials, 2023-24

Leader

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Lecturer

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Timing and Structure

Lent term. 13 lectures. Assessment 100% coursework

Prerequisites

Prior knowledge of 3C7 and 3D7 is beneficial but not required

Aims

The aims of the course are to:

- Introduce the state-of-the-art concepts and theories for deep learning and neural networks.
- Describe the main methods of constructing learning-based partial differential equation solvers with illustrative examples on Darcy flow and elasticity.
- Explain the concept and theory of path dependency (memory) and multi-scale modelling, with application of the data-driven methods for discovering and approximating constitutive models for various materials.

Objectives

As specific objectives, by the end of the course students should be able to:

- Understand the principles of applying data-driven methods to physical problems.
- Design, implement and train learning-based PDE solvers for stress analysis.
- Discover non-linear, path-dependent material models from data using deep neural networks.

Content

Mechanics and materials are gradually becoming data-rich due to rapid advances in experimental science and high-performance multiscale computing. There has been a growing interest in the field of solid mechanics for developing data-driven and learning-based methods to characterize, understand, model, and design material/structural systems. With data-driven approaches, it is possible to remove/relax the need for ad hoc constitutive models for describing the material behavior, to achieve fast multi-scale computation for structures as well as to generate optimal designs. This module will introduce a wide spectrum of data-driven/learning based methods that have been developed and used in mechanics and materials, with an emphasis on developing a working understanding of how to apply these methods in practice.

Syllabus

Neural network basics (4L)

a. Basic concepts in supervised and unsupervised learning.
b. Fully connected neural network, stochastic gradient descent.
c. Advanced neural network architectures: convolution neural network, Res-net, U-net.
d. Python for machine learning and pytorch tutorial.

Machine learning for PDEs: Physics Informed Neural Networks and Neural Operators (4L)

a. Physics informed neural networks for ODE and PDE.
b. Learning the solution operator of PDE with Neural Operators.
c. Fourier and Graph Neural Operators.

Machine learning for path dependent problems and learning based multi scale modeling (4L))

a. Machine learning methods for memory and path dependence.
b. Long Short Term Memory and Transformer networks.
c. Multiscale modeling and Recurrent Neural Operator.
d. Generative modeling methods.

Data-driven methods in mechanics and beyond - guest lecture (1L)

a. Neural operators in climate change - the earth 2 project.
b. Researches in NVDIA.

Coursework

Course work 1: Neural network and Pytorch basics

Description: This course work consists of two problems:

(i) Regression problem: Student will be provided with measured stress-strain data for two unknown elastic materials. Students are asked to build, train and validate a neural network model for approximating the constituitive relationship of the material. They will use basic fully connected neural network.

(ii) Classification problem: Student will be asked to design, implement and train a neural network classifier that predicts whether a truss structure (Effiel tower) will collapse under certain external pressures. They will investigate the use of both basic fully connected neural network as well as advanced deep Res-net, and assess the netowrks performance.

Format: 1 individual report

Course work 2: Learning based stress analysis

Students will be asked to solve a 2D elasticity problem for a plate with hole under bi-axial loading using Physics Informed Neural Networks. They will also be asked to design and implement a Fourier Neural Operator to learn the solution operator of the Darcy flow problem.

Format: 1 individual report

Course work 3: Learning based constitutive model for anisotropic solids

Description: Students will be asked to come up with novel designs of neural network architectures that can represent memory/path-dependency of solid materials. They will be given a micro-mechanical unit-cell problem governed by visco-elasticity, and are expected to train their neural networks to find the homogenized macroscopic constitutive model, together with the hidden internal variables that captures the memory of deformation path at the macroscopic scale.

Format: 1 individual report

Booklists

Please refer to the Booklist for Part IIB Courses for reference to this module, this can be found on the associated Moodle course.

Examination Guidelines

Please refer to Form & conduct of the examinations [3].

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