Machine Learning in Geomechanics: Foreword

When discussing about artificial intelligence (AI), some basic questions are immediately emerging such as: what AI is? how does it work? Behind this popular term, there is a collection of methods of Applied Mathematics that allow the computer to learn and identify patterns in data. This collection of methods is called Machine Learning (ML) and it is the target of ALERT's 2023 Doctoral School.

In combination with the tremendous increase of the computational power, Machine Learning has led to incredible achievements in many disciplines of science and technology. These achievements were that striking that some researchers believe that ML could become a turning point for humanity, as the discovery of fire was for our far ancestors!

Until the sixties, the scientific development has been characterized by the so-called "linear physics" and by modeling represented by analytical equations solved explicitly by the available mathematical tools giving rise to analytical solutions. The field of problems which can be solved in this way is, of course, precious, but very limited.

Then the numerical revolution, based on powerful numerical methods and computers, allowed to solve numerically a great variety of problems, which can be described by a known system of equations. Many limits of this methodology are known due to the abundance of non-linear processes in nature, chaos and complexity. In any case, Numerical Analysis, another branch of Applied Mathematics, has immensely enlarged the class of problems that can be solved today.

However, the numerical solutions of these sets of non-linear equations can be computationally very intensive or even impossible. Moreover, many problems in engineering are hard to describe by a set of equations. Machine Learning tools provide promising methods for addressing both those problems.

Another aspect of ML algorithms is their ability to solve very complex problems in a "creative" manner. One characteristic example of creativity was shown when the machine won the world champion of the Go game, which was invented a long time ago in China. Differently from chess, in which the computer can predict the game evolution several moves in advance, in Go the number of possible moves is extremely large (higher than the number of atoms in the known universe). Therefore, it is necessary to follow creative strategies. Indeed, the machine, "AlphaGo", has shown that it is able to carry out novel strategies that surprised even the best human players in the world.

All these methods of Machine Learning, give new powerful tools to scientists and engineers and open new perspectives in Geomechanics. The target of this volume is to demystify Machine Learning, to present its main methods and to show some examples of applications in (geo-)mechanics. Most of the chapters of the volume were drafted having in mind to provide a pedagogical introduction to the most important methods of ML and to uncover the fundamental notions behind them.

The volume is organized in ten chapters:

The first chapter, "Overview of Machine Learning", is the introductory chapter of this volume. In this chapter we explain how the machine can learn, we show a classification of the main methods in Machine Learning, we outline some applications of ML in Geomechanics and we highlight its limitations.

The second chapter, "Introduction to regression methods", focuses on regression, which is one of the fundamental pillars of supervised Machine Learning. In this chapter we introduce the essential concepts in regression analysis and methods, by providing hands-on, practical examples.

The target of the third chapter, "Unsupervised Learning: Basic Concepts and Application to Particle Dynamics", is twofold. The first part of this chapter is devoted to the description of the basic concepts of the most popular techniques of unsupervised learning. The second part illustrates an application of unsupervised learning to the discovery of patterns in particles dynamics.

The fourth chapter, "Classification Techniques in Machine Learning", aims at describing what the problem of classification in Machine Learning is and illustrates some of the methods used for solving it, without resorting to Artificial Neural Networks. Hands-on examples are given and Active Learning is discussed.

Chapter five, "Data-Driven Modeling in Geomechanics", presents the theoretical framework of the so called data-driven computational mechanics. Furthermore, it shows some of its applications for the solution of problems involving Cauchy and Cosserat continua with elastic and inelastic materials, which, naturally, represent common descriptions of geomaterials.

The sixth chapter, "Non-Euclidean machine learning for geomechanics", is intended to provide a concise review on how to train, verify and validate constitutive models enhanced by graph-theoretic data. The use of graph convolutional neural networks for constitutive modeling, material design, and the solution of inverse problems is discussed.

The next two chapters, "Artificial Neural Networks: layer architectures, optimizers and automatic differentiation" and "Artificial Neural Networks: advanced topics" provide a comprehensive introduction to Artificial Neural Networks (ANN). Several hands-on examples are given to help the reader grasp the main ideas and tools of the most important ANN architectures. More advanced topics are also discussed and the connection of ANN with information theory is made.

Chapter nine "Physics-informed and thermodynamics-based neural networks" shows how to inject prior knowledge into deep learning algorithms. Using various examples, we present Physics-Informed Neural Networks for the discovery of partial *differential equations and Thermodynamics-based Artificial Neural Networks for the discovery of constitutive models of complex, inelastic materials.*

The last chapter, "Introduction to Reinforcement Learning with Applications in Geomechanics", presents the basic concepts of Reinforcement Learning, which enables the development of software agents that are capable of making optimal decisions in dynamic and uncertain environments. The chapter closes with two applications of Reinforcement Learning in Geomechanics.

We deeply thank all the authors of this volume for their comprehensive contributions and their effort to present complex notions in a pedagogical manner. We hope that the chapters provide a valuable introduction to Machine Learning in Geomechanics.

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