

Lecture 01: Introduction

ENEE 691 – Machine Learning and Photonics @ UMBC

Ergun Simsek, Ph.D. and Masoud Soroush, Ph.D.

January 31, 2023

1 Welcome to "Machine Learning and Photonics"

In today's lecture¹, we will explain what photonics and machine learning are about, what you should expect from this introductory course. After a brief introduction, we will start reviewing some basic numerical, mathematical, and statistical concepts that will be used throughout the course.

1.1 Hello Photonics

Photonics is a field of study that deals with the generation, detection, transmission, manipulation, and, control of light. Photonics is interdisciplinary and encompasses multiple areas of study including physics, electrical engineering, and materials science and it plays a vital role in modern technology. Many everyday devices such as smartphones, tablets, laptops, and televisions use photonics. It is also used in advanced technologies such as fiber-optic communication systems, solar-cell-based renewable energy solutions, driverless transportation devices, precise manufacturing facilities, and laser-based medical treatments such as eye surgery, cancer treatment, and laser hair removal (ouch!).

Despite its many benefits, there are still many challenges facing the photonic market today such as the integration of photonics into existing technologies, which requires the development of new materials and fabrication techniques to create devices that can handle the unique properties of light. The high cost of producing photonic devices is still a significant barrier to entry for many small- and mid-sized companies. Another challenge facing the photonic market is the need for more advanced and efficient systems. With the rapid growth of data and the increasing demand for faster and more reliable communication systems, there is a need for new technologies that can handle the increased demand. This requires ongoing research and development in areas such as photonics-based computing and photonics-based data storage.

¹ This product is a property of UMBC, and no distribution is allowed. These notes are solely for your own use, as a registered student in this class.

Most fundamental and/or important photonic components and devices

1. Lasers (to produce very narrow beams of light to be used in a wide range of applications, including telecommunications, medicine, and manufacturing)
2. Photodetectors (to detect and measure light for example in cameras, optical communication systems, and sensors)
3. Fiber optics (to transmit light over long distances in telecommunications and data transmission systems)
4. Modulators (to control the intensity, phase, or polarization of light to be used in telecommunications and data transmission systems)
5. Sensors (that uses light to detect molecules)
6. Optical Frequency Combs (to measure and control very high-frequency electromagnetic waves—such as light—as if they were radio waves)
7. Mirrors and lenses (to reflect or focus light to be used in imaging and optical communication systems) and optical filters (to separate or combine different wavelengths of light to be used in imaging and spectroscopy)

Metals, semiconductors, and dielectric materials all can be found in different photonic components mentioned above. Some special types of materials can be mentioned as

1. Nonlinear optical materials (that change their optical properties in response to light and are used in optical computing and telecommunications)
2. Metamaterials and Photonic crystals (artificial materials with a periodic structure that controls the flow of light and are used in sensing, optical communication, and photovoltaics)
3. Quantum dots (tiny semiconductor particles that can be used to create new types of light sources for quantum computing and biotechnology)

1.2 What Is Machine Learning?

Data science is a field that combines knowledge and tools from computer science, statistics, and domain expertise in order to extract insights and knowledge from data. The following picture depicts different steps of the life cycle of data science projects. A data science project starts with a set of research questions to define goals and objectives to achieve. In the next step, you need to acquire an understanding (domain knowledge) of your project in order to define your objectives. Note that your objectives must be **SMART** (*i.e.* Specific, Measurable, Achievable, Relevant, and Time-bound). Once you have defined your objectives, you will then look for relevant data. The data must be relevant to your research questions and objectives. After identifying your data sources and acquiring the necessary understanding of your data, the next step is data preparation. This step includes the data wrangling process that we will cover briefly next week. The focus of the first half of this course is exactly on the next two steps of the life cycle, namely **Modeling** and **Evaluation**. Machine learning concerns these two steps. However, if you are still wondering what machine learning is, here is a definition:

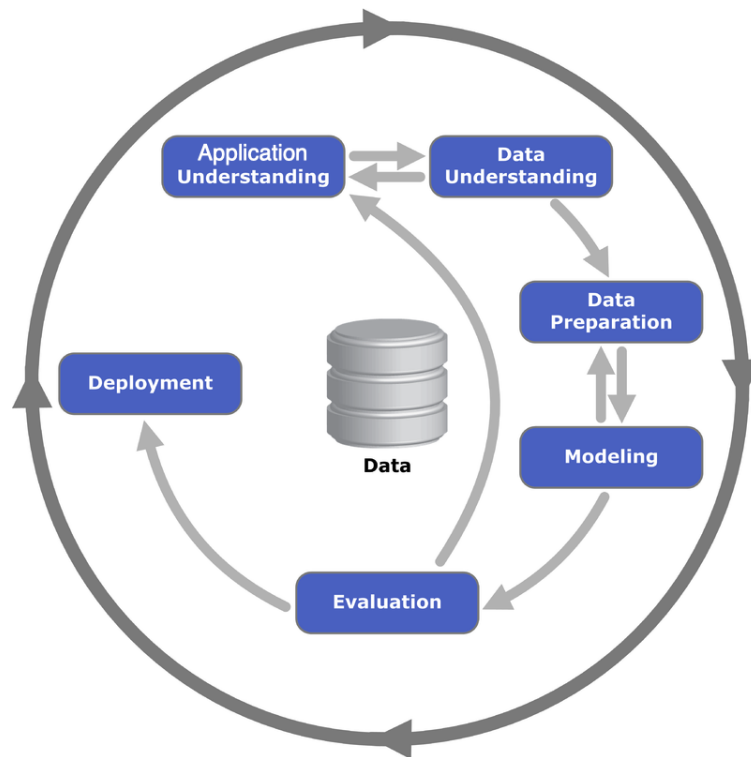


Figure 1: Life-cycle of a typical data science project.

Machine Learning is a subcategory of artificial intelligence, that refers to the process by which computers develop pattern recognition, or the ability to continuously learn from and make predictions based on data, then make adjustments without being specifically programmed to do so.

Machine learning is innately data driven, and data is at the core of machine learning.

The goal of machine learning is to design general-purpose methodologies to *extract valuable patterns from data*, ideally without much domain-specific expertise. To achieve this goal, we *design models* that are typically related to the process that generates data, similar to the dataset we are given. To adjust the parameters of the model to their optimal values, the *model has to learn from data*. A model is said to *learn from data* if its performance on a given task improves after the data is taken into account. The goal is to find good models that generalize well to yet unseen data (that we may care about in the future).

Learning can be introduced as a method to automatically find patterns and structure in data by optimizing the parameters of the model. However, this optimization of the parameters of the model shouldn't be confused with the numerical optimization. Numerical optimization is the process of finding the best solution to a mathematical problem by iteratively adjusting input variables to minimize or maximize an objective function. Numerical optimization is focused on finding the best solution to a mathematical problem, while machine learning is focused on training a computer system to make predictions or decisions based on data. In other words, ML uses numerical optimization techniques to determine the parameters of a model but they are not the same thing!

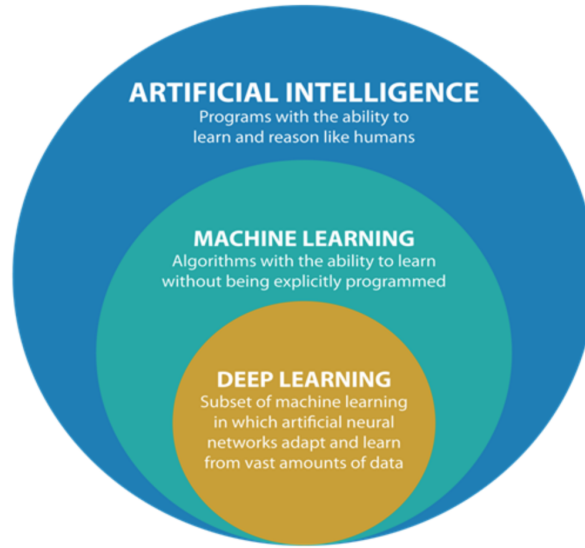
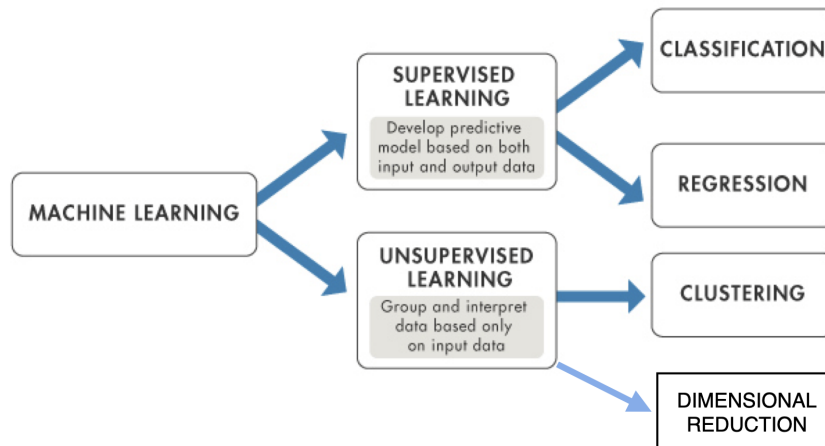


Figure 2: Artificial intelligence vs. machine learning vs. and deep learning.

In statistical and machine learning, we deal with two major types of learning: **Supervised learning** and **Unsupervised learning** as depicted below. In a supervised learning, we have a response variable (or **target variable**), whereas in an unsupervised learning, there is no response/target variable. Depending on the nature of the target variable in a supervised learning, we have two types of machine learning algorithms. If the target variable is a **quantitative variable**, we have a regression problem, and if the target variable is **qualitative/categorical**, then we have a classification task. Roughly speaking, regression is the *process of predicting a value for a continuous target variable*, and classification is the *process of predicting a value for a categorical target variable*.



In unsupervised learning, there exists no target variable (or the target variable is dismissed). The goal is to analyze the *unlabeled data* and discover patterns in the dataset. Two of the common and popular algorithms used in unsupervised learning are **Clustering** and **Dimensional Reduction**.

In order to develop machine learning algorithms and obtain a solid understanding from their

underlying mechanisms, one must be equipped with certain mathematical and statistical tools. In a nutshell, one should be familiar with basics of *calculus*, *linear algebra*, and *basic statistics*. In calculus, we specifically need to know basics of function optimization. In linear algebra, we need to feel comfortable with matrix algebra and eigenvalue problems. Finally, we should be fairly comfortable with the tools of basic statistics. In the first two lectures, we will briefly review some important subjects from these three fields. The following figure² indicates some of the common mathematical and statistical tools used in machine learning.

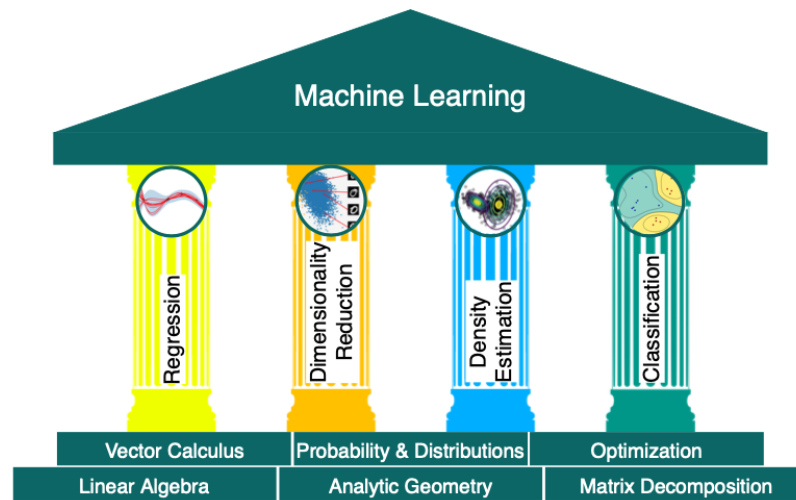


Figure 3: Why should we study math to understand how ML works?

Side Question: While the necessary mathematical and statistical prerequisites of machine learning algorithms were known for a long time, why did machine learning receive an apt attention in the past few decades?

There are several important characteristics that one should consider when a machine learning algorithm is adopted:

- **Power and Expressibility:** Machine learning algorithms differ in the richness and complexity of the models they support. Greater expressive power provides the possibility of more accurate models, as well as the dangers of overfitting.
- **Interpretability:** Powerful algorithms sometimes produce models that are very accurate, but no human-readable explanation of why they work the way they do. Interpretability is an important property of a model, and some data scientists are happier to take a lesser-performing model they understand over a slightly more accurate one that they don't.
- **Ease of Use:** Certain machine learning methods feature relatively few parameters or decisions, meaning they are easy to work with. In contrast, some machine learning algorithms provide much greater scope to optimize the performance with the proper settings.
- **Training Speed:** Machine learning algorithms differ greatly in how fast they fit the necessary parameters of the model, which determines how much training data you can afford to use

² Source: M. P. Deisenroth, A. A. Faisal, and C. S. Ong, *Mathematics for Machine Learning*, Cambridge University Press (2020).

in practice. Don't forget that your computational power is limited!

- **Prediction Speed:** Machine learning algorithms differ in how fast they make classification decisions on a new queries.

The above characteristics will not be equally important in every data science problem you intend to solve. In each problem, you have to decide where to put your emphasis based on the goals of your project and your available resources.

1.3 Machine Learning for Photonics

Machine learning algorithms can play a crucial role in helping to develop new photonic technologies by providing a way to analyze and interpret large amounts of data, as well as by enabling the automation of complex design processes.

One of the key areas where machine learning algorithms can be applied to photonic technology development is in the field of optical communication systems. In these systems, information is transmitted using light waves, and the ability to control and manipulate these light waves is crucial for achieving high-speed data transmission. Machine learning algorithms can be used to analyze large amounts of data from optical communication systems, such as the transmission of light through different materials and the behavior of different types of optical fibers. This data can then be used to optimize the design of optical communication systems, resulting in faster and more efficient data transmission.

Another area where machine learning algorithms can be applied to photonic technology development is in the field of optical sensing. Optical sensors can be used to detect a wide range of physical and chemical phenomena, such as temperature, pressure, and chemical composition. However, the design of these sensors can be complex, and it can be difficult to optimize their performance. Machine learning algorithms can be used to analyze data from optical sensors, such as the response of different materials to different types of light. This data can then be used to optimize the design of optical sensors, resulting in improved performance and sensitivity.

In addition, machine learning algorithms can also be used to automate the design of photonic devices. The design of photonic devices can be a complex and time-consuming process, and it can be difficult to optimize the performance of these devices. Machine learning algorithms can be used to analyze data from photonic devices, such as the response of different materials to different types of light. This data can then be used to optimize the design of photonic devices, resulting in improved performance and efficiency. We call this approach "forward photonic design". There is also the "inverse photonic design," in which we can use adjoint method or generative adversarial networks (GANs) to determine the geometry and material properties of the device that will produce a desired performance such as the optical response, bandwidth, quantum efficiency, phase noise, etc.. We will discuss these methods in the second half of the course.

1.4 Photonics for Machine Learning

Photonics can help to improve the speed, accuracy, and scalability of machine learning algorithms, making them more useful for a wide range of applications. For example,

- **Optical computing:** Photonics can be used to perform computations at high speeds and with low power consumption. This can improve the performance of machine learning algorithms and enable more complex models to be trained.

- Optical sensing: Photonics can be used to create sensors that can detect a wide range of physical phenomena, such as light, temperature, and motion. These sensors can be used to gather data for machine learning algorithms, allowing them to make more accurate predictions.
- Optical communication: Photonics can be used to transmit data between devices at high speeds, which can improve the performance of distributed machine learning systems.
- Optical Neuromorphic computing: Photonics can enable the development of neuromorphic computing systems that mimic the way the human brain processes information. This can improve the ability of machine learning algorithms to process complex, unstructured data.

In the third and last part of this course, we will discuss these very recent and exciting advancements in computing/ML with light.

Now, let's start with some basic concepts in numerical analysis.