Course Title: Information Geometry and Its Applications in Machine Learning and Beyond

Course Code: [To be assigned]
Instructor: Professor Amine Aboussalah
Term: [Spring Term, 2025]
Class Time: [To be determined]
Location: [To be determined]
Office Hours: [To be determined]
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Course Description:

This course offers an advanced, research-oriented exploration of **Information Geometry** and its significant applications across **Machine Learning**, **Statistics**, and various real-world domains. Information Geometry provides a mathematical framework to understand the underlying geometry of probability distributions and how it impacts learning algorithms, statistical models, and other advanced topics in computational fields. The course aims to equip students with both theoretical knowledge and practical tools to investigate cutting-edge research questions.

As a research-oriented course, both PhD and MS students will engage deeply with foundational concepts and investigate state-of-the-art research developments in the field. The course will culminate in individual or collaborative research projects that advance the field of Information Geometry, with a focus on applications in machine learning, optimization, data science, and related areas

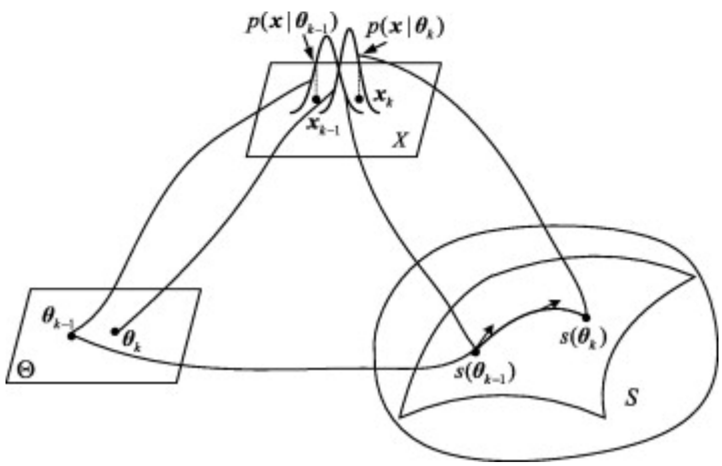

Illustration of the relation between parameter, measurement and the corresponding statistical manifold. Yongqiang Cheng, Xuezhi Wang, Mark Morelande, Bill Moran, Information geometry of target tracking sensor networks, Information Fusion, Volume 14, Issue 3, 2013, Pages 311-326, ISSN 1566-2535, https://doi.org/10.1016/j.inffus.2012.02.005.

Prerequisites:

- Machine Learning (ML)
- Mathematical Foundations in Probability, Statistics, and Linear Algebra
- Familiarity with Optimization Techniques
- Some exposure to Differential Geometry (helpful but not required)

Course Objectives:

By the end of this course, students will be able to:

1. Understand and apply the principles of Information Geometry to a variety of Machine Learning models.
2. Analyze complex systems using geometric structures of statistical manifolds.
3. Formulate and solve optimization problems in learning tasks from an information-geometric perspective.
4. Conduct original research in Information Geometry, contributing novel insights to the field.
5. Engage in interdisciplinary applications of Information Geometry in fields like Finance, Physics, Signal Processing, and more.

Course Structure and Topics:

The course is structured into **four key modules**, with each module emphasizing different aspects of Information Geometry and its applications.

Module 1: Foundations of Information Geometry (Weeks 1-3)

- Introduction to Information Geometry: A Historical Overview
- Statistical Manifolds: Riemannian Geometry of Probability Distributions
- Divergences and Distance Measures: Kullback-Leibler, Bregman, and Fisher Information
- Dual Geometries: Amari's α-connections and its Role in Learning Theory

Module 2: Information Geometry in Machine Learning (Weeks 4-6)

- Information Geometry of Neural Networks
- Geometric Methods for Optimization in Deep Learning
- Fisher Information and Natural Gradient Descent
- Entropic Regularization and Information-Theoretic Constraints in ML

Module 3: Advanced Topics and Current Research (Weeks 7-10)

- Information Bottleneck and Over-squashing in Graph Neural Networks
- Information Geometry of Reinforcement Learning Algorithms

- Applications in Financial Engineering: Modeling Uncertainty and Risk using Geometrical Approaches
- Current Research in Information Geometry (Guest Lectures/Research Paper Discussions)

Module 4: Research Projects and Presentations (Weeks 11-14)

- Independent/Group Research on Selected Topics
- Research Paper Writing and Peer Review Process
- Project Presentations: Defending and Critiquing Research Contributions
- Wrap-up and Future Directions

Assessment and Grading:

Class Participation and Discussions: 5%

- Active participation in class discussions and group activities is required.

Case Study Presentation: 25%

- Students will engage in a case study divided into four weekly assignments, focusing on a selected topic. Topics will be assigned in class, and students are expected to present their findings progressively, integrating both theoretical and practical aspects of Information Geometry.

Research Paper Review and Presentation: 20%

- **PhD Students:** Each student will review a seminal paper in the field of Information Geometry, provide a summary, and present it to the class.
- **MS Students:** Students will form groups of 2 or 3 to review a seminal paper in the field of Information Geometry, prepare a summary, and present their findings to the class.

Final Research Project: 50%

- **PhD Students:** The final project should demonstrate original contributions to the field, present an interesting application, or provide a thorough literature review of a specific subtopic. Projects may involve theoretical exploration, algorithm development, or application-based studies. Deliverables include a research paper (10-15 pages) and a class presentation. This is an individual assignment.
- **MS Students:** The final project should consist of a comprehensive literature review of a specific subtopic in Information Geometry. This may include theoretical exploration, algorithm development, or application-based studies. Deliverables include a final report (10-15 pages) and a class presentation. This is a group assignment, with teams of 2 or 3 students.

Textbooks and Reading Material:

- **Primary Textbook:**
    - Shun-Ichi Amari, "Information Geometry and Its Applications," Springer, 2016.
- **Additional References:**
    - Amari, S., "Differential-Geometrical Methods in Statistics," 1985.
    - Nielsen, F. (2020). "An Elementary Introduction to Information Geometry." Entropy, 22(10), 1100.
    - Joel W. Robbin, Dietmar A. Salamon (2002). "Introduction to Differential Geometry." ETH Zurich.
    - Cover, T. M., Thomas, J. A., "Elements of Information Theory," 2nd edition, Wiley, 2006.
    - Recent research papers from top Machine Learning and Information Theory conferences (NeurIPS, ICML, ICLR, etc.)

Research-Based Approach:

This course emphasizes **independent research** and encourages students to explore open problems in Information Geometry. Students will be required to:

- Engage with current literature, identify gaps, and formulate research questions.
- Collaborate on projects and share findings in a seminar-style format.
- Submit a final research paper that may be suitable for conference submission or publication.

Course Policies:

- **Attendance:**
  Regular attendance is expected. If you must miss a class, inform the instructor in advance.
- **Late Submission Policy:**
  Late submissions will incur a penalty unless prior approval is granted.
- **Academic Integrity:**
  Strict adherence to NYU's policies on academic honesty. Plagiarism or cheating will result in disciplinary action.

Schedule Overview:

Week	Topic	Key Activities
1-3	Foundations of Information Geometry	Lectures, Problem Sets
4-6	Information Geometry in Machine Learning	Case Study Presentations and Discussions
7-10	Advanced Topics	Research Paper Presentations and Discussions, Guest Lectures
11-14	Research Projects and Presentations	Research Paper Submission and Presentation