**WORKSHOP ON DATA-DRIVEN AND MODEL-BASED TOOLS FOR COMPLEX FLOWS AND COMPLEX FLUIDS**

ROME – DEPT PHYSICS UNIVERSITY OF TOR VERGATA
JUNE 3-7 2024 AULA GRASSANO

| | Mon 3 | Tue 4 | Wed 5 | Thu 6 | Fri 7 |
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| | | | | | |
| 09.00-11.00 | Lectures A1-A2 | Lectures A3-A4 | Lectures A5-A6 | Hands-on C | Hands-on A |
| 11.00-11.30 | coffee | coffee | coffee | coffee | coffee |
| 11.30-13.30 | Lectures B1-B2 | Lectures B3-B4 | Lectures B5-B6 | Hands on C | Hands on A |
| 13.30-14.30 | Lunch | Lunch | Lunch | Lunch | Lunch |
| 14.30-16.30 | Lectures C1-C2 | Lectures C3-C4 | Lectures C5-C6 | Hands on B | summary |
| 16.30-17.30 | | | | Hands-on B | summary |

## A. Lecture series on Kinetic Theory and Applications to Fluid Mechanics
## Fabio Guglietta (Dept. Physics University of Rome Tor Vergata)

**Short description:**
This six-lecture course delves into kinetic theory and its application in computational fluid dynamics. The course begins with an introduction to kinetic continuum theory, showing its connections with fluid mechanics. We then move on to the lattice kinetic theory, introducing the Lattice Boltzmann equation. In recent years, various Lattice Boltzmann (LBM) methods have been used: we present the most important ones, showing state-of-the-art methods and results. Particular attention is given to fluid-structure interaction (FSI) problems. In particular, we show the Immersed Boundary Method (IBM) and its integration with LBMs. The final part of the course is dedicated to the applications of IB-LBM methods.

**Preliminary program:**
1. **Continuum kinetic theory: Boltzmann Equation**
- After providing a summary of the continuum kinetic theory, we write the Boltzmann equation and we focus on the collision operator. We then show the link with the equations of fluid mechanics (Navier-Stokes equations).
2. **Lattice kinetic theory: Lattice Boltzmann Equation**
- The kinetic theory is the cornerstone of the Lattice Boltzmann Methods. We sketch how the lattice description of the kinetic theory can be obtained, and we write the Lattice Boltzmann Equation. Again, the link with the fluid mechanics is shown.
3. **Overview of Lattice Boltzmann Methods (LBMs).**
- We show an overview of the most important LBMs employed, depending on the problem one is interested in. We highlight different features and implementations.
4. **Fluid-Structure Interaction: immersed boundary method (IBM) and hybrid IB-LBM.**
- The IBM is usually employed within different fluid solvers to handle the Fluid-Structure Interaction (FSI). After overviewing the IBM, we show how it couples with the LBM, highlighting pros and cons of the method.
5 & 6. **Applications of IB-LBM.**
- In this couple of lectures, we overview the state-of-the-art literature in the context of IB-LBM, with a special focus on the simulation of soft particles (drops, capsules, living cells, etc.).

**Hands-on section:**
We go through the implementation of the simplest LBM on GPUs, and perform basic numerical simulations to show some relevant results in fluid mechanics.

## B. Lecture series on Optimal Policies for Lagrangian Turbulence
## Robin Heinonen (Dept. Physics University of Rome Tor Vergata)

**Short description:**
The trajectories of particles advected by turbulent flows exhibit chaos and intermittency. These phenomena present challenges for several interesting control problems, including the point-to-point navigation of the flow by an active swimmer, and the tracking of sources of odors and other passive scalar cues. In this short course,

we discuss a few such control problems and introduce several tools for tackling them. The language of Markov decision processes will be introduced and used to develop the theory of optimal control via the Bellman equation. We will also discuss partial observability, reinforcement learning, and several heuristic strategies for the problems of interest.

**Preliminary program:**
1. **Lagrangian turbulence: physics and challenges**
 - Sketch some of the physics of lagrangian turbulence, advection of passive scalars, and odor landscapes. Discuss interesting navigation problems: swimming, olfactory search. What makes them hard?
2. **Markov decision processes**
- Introduce MDP formalism, including concepts of actions, states, rewards, policy. Cast several examples into this language, including swimming problems.
3. **The Bellman equation**
- Introduce value function, Q function. Derive Bellman equation. Also discuss HJB equation. Discuss solution by dynamic programming, value iteration.
4. **Partial observability**
- Discuss POMDP, Bayesian inference. Exploration/exploitation tradeoff, multi-armed bandits. Cast olfactory search as POMDP. Discuss solution of POMDP e.g. by point-based value iteration, curse of dimensionality.
5. **Reinforcement learning**
- Primer on reinforcement learning. Q-learning, SARSA, policy gradient methods. Intro to deep reinforcement learning. Show application to swimming.
6. **Heuristics and extra topics**
- Introduce heuristics for swimming, olfactory search. Summary of pros/cons of various approaches (optimal control, RL, heuristics). Time permitting: discuss impact of correlations on POMDP.

**Hands-on section:**
Students will be given lagrangian particle data and guided to construct, benchmark, and visualize a few heuristic policies for olfactory search.

## C. Lecture series on Data-Driven Tools for Eulerian Turbulence
## Michele Buzzicotti (Dept. Physics University of Rome Tor Vergata)

**Short description:**
This lecture series is at the intersection of turbulence challenges and modern machine-learning solutions. Starting from Eulerian and Lagrangian turbulence theory, we will move to sophisticated data-driven strategies. The focus will be on extending conventional methods with machine learning and developing algorithms that use both empirical data and fundamental physics to improve their results.

**Preliminary program:**
1. **Eulerian and Lagrangian Turbulence: From Theory to Geophysical Applications** • An introduction to the physical problem of turbulence and its relevance to geophysical studies.

2. **Standard Methods for State Reconstruction from Partial Observations** • Discussion of data-driven methods such as Proper Orthogonal Decomposition and Gaussian Regression Progress, as well as equation-based approaches such as nudging.

3. **Generative Adversarial Networks (GANs) in Machine Learning** • Fundamentals of GANs and discussion of how they can be an improvement over traditional turbulent flow reconstruction methods.

4. & 5. **Diffusion Models** • Examination of advanced generative methods and their cutting-edge results in generating and reconstructing Eulerian and Lagrangian turbulent data.

6. **Physics-Informed Machine Learning** • Demonstrating how machine learning can leverage physical insights to improve data reconstruction and reduce reliance on large datasets.

**Hands-on section:**
We go through the implementation of a GAN training algorithm to reconstruct turbulent flows on a rotating frame.