UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Galaxy Evolution in Cosmic Structures A

2425-1-113R-04

Aims

1. Introduce students to cosmological hydrodynamical simulations of galaxy formation.
2. Equip students with the skills to independently explore existing numerical simulations and run new ones using state-of-the-art, publicly available numerical codes.
3. Introduce advanced data analysis methods to enable efficient analysis of large datasets.

Contents

The course is structured into four modules, each aimed at achieving the following outlined objectives:

1. **Introduction to Numerical Simulations:** Overview of numerical simulations for astrophysical objects and hands-on analysis of state-of-the-art simulations using Python.
2. **Creating Initial Conditions and Running Simulations:** Introduction to generating initial conditions and running cosmological simulations with state-of-the-art codes.
3. **Advanced Data Structures:** Exploration of advanced data structures to optimise the analysis of large simulations and big data.
4. **Visualisation Techniques:** Introduction to visualisation techniques for interpreting and presenting results from state-of-the-art simulations.

Detailed program

The course is structured into four modules, designed to equip students with the essential skills needed to undertake a research project using numerical astrophysics techniques. While the focus will primarily be on cosmological simulations of galaxy formation, we will also encourage discussions on applying these techniques to other astrophysical problems.

1. **Module 1** provides an introduction to numerical simulations, with a specific emphasis on cosmological simulations of galaxy formation. This module will cover the following topics:

- The basics of numerical simulations and initial conditions.
- Numerical techniques for integrating the equations of motion and fluid dynamics.
- The role of subgrid models in describing star formation processes.
- An overview of current state-of-the-art numerical simulations.
- A look at upcoming simulations of galaxy formation.
- Key challenges in the field.

This module includes hands-on exercises centred around the analysis of cutting-edge numerical simulations. Students will analyse a pre-existing simulation provided in class, engaging in exercises that closely resemble the real-world analysis conducted by numerical cosmologists in a research setting.

2. **Module 2** introduces the concept of cosmological initial conditions and explores existing codes used to generate them. We will discuss different types of initial conditions, comparing the advantages and disadvantages of various approaches. Additionally, we will introduce a numerical simulation code, allowing students to run their own cosmological simulations.

The key topics covered in this module include:

- Methods for generating cosmological initial conditions: A Gaussian random field and the power spectrum, with practical application using the MUSIC code.
- Determining the largest simulation feasible within given computational resources.
- Running a simulation, demonstrated through the massively parallel GADGET-4 code.

This module includes hands-on exercises focused on the basic analysis of the simulations created. The exercises aim to provide students with the tools to assess whether the simulation results are valid or have been affected by numerical errors.
To ensure a smooth workflow, we will provide the necessary numerical codes and a Docker containers, which will manage the compilation process and required packages without disrupting the exercises.

3. **Module 3** aims to give students a foundational understanding of how advanced data structures can significantly improve the efficiency of analysing large datasets. We will demonstrate how the proper organisation of simulation data can result in substantial speed improvements during analysis.

Key data structures covered in this module include:

- Linked Lists: Since analyzing numerical simulations often requires efficient spatial access to data clusters within the simulation volume, we will introduce linked list data structures. These can reduce the complexity of linear searches from O(NlogN) to O(1) in the best-case scenario.

- Hash Tables: To efficiently cross-match data across multiple temporal outputs in simulations, we will explore Hash Tables, which reduce the complexity of linear searches for cross-matching from O(N) to O(1).

Students will learn the fundamentals of these algorithms and engage in hands-on exercises to implement and apply these data structures to existing numerical simulations. Through this, they will analyse the speed improvements compared to standard algorithms that do not use optimised data structures.

4. **Module 4** will focus on *state-of-the-art* visualisation techniques for cosmological hydrodynamical simulations. We will address the challenges of visualising simulations and introduce algorithms that efficiently transform particles into smooth, visually compelling maps.

Key concepts to be covered include:

- Particles in cells: Understanding shot noise and the importance of normalisation in data.
- Smooth maps: Techniques for generating smooth visual representations of simulations.
- Clustering techniques for particles: Applying Smooth Particle Hydrodynamics (SPH) techniques for visualisation with the py-sphviewer code.
- Creating simulation movies: Key aspects such as the movie length, desired frame rate, and interpolation techniques.

The module will include hands-on exercises where students apply the py-sphviewer code to an existing simulation. Through this, they will explore various visualisation techniques and understand how these methods can be crucial for measuring astrophysically relevant properties.

Prerequisites

Students should have a basic understanding of cosmology and physics at the MSc level. A laptop is also required for participation in the hands-on exercises.

Teaching form

The course will consist of electronic presentations covering the key concepts of each module, followed by hands-on exercises. It will run over four weeks, with two 2-hour lectures per week. Each module will be completed over the course of one week, with sufficient in-class time provided for students to finish the module's exercises within that week.

Textbook and teaching resource

1. The required material will be provided during the lessons, both as electronic presentations and shared files.
2. The simulation data and required software will be provided during the lectures.

Semester

The course will be likely offered during the first semester of the 2024/2025 academic year, with a likely start in November.

Assessment method

The final assessment will consist of a written report summarising the findings of a proposed exercises, where students will apply the techniques studied throughout the course.

Office hours

By appointment

Sustainable Development Goals

QUALITY EDUCATION | INDUSTRY, INNOVATION AND INFRASTRUCTURE