

# Computational Physics Lectures:

## Introduction to the course

Morten Hjorth-Jensen<sup>1,2</sup>

<sup>1</sup>Department of Physics, University of Oslo

<sup>2</sup>Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University

2018

### Overview of first week

- Wednesday
  1. Presentation of the course, aims and content
  2. Introduction to C++ programming and numerical precision. Discussion of first project
  3. Numerical differentiation and loss of numerical precision (chapter 3 lecture notes)
- Computer lab: Friday
  1. The first two weeks we focus on simple programming tasks, start to look at project 1 and to set up the software [Git](#) and a repository at [Github](#) as well as [Qt Creator](#) as one possible IDE. This week we discuss how to set up Git and obtain a Github account.

Please take the survey. Hopefully this information will allow us to tailor the course to your interests and background.

### Reading suggestions and exercises

- Read sections 2.1-2.5 and 3.1-3.2 of lecture notes:
  - Introduction to C++ programming

- Numerical precision and C++ programming (chapter 2 of lecture notes)
- Numerical differentiation and loss of numerical precision (chapter 3 lecture notes)
- Work on warm up exercise to demonstrate several programming elements and/or start looking at project 1

## Lectures and ComputerLab

- Lectures: Most likely Wednesdays from 4pm to 530pm (As of now not determined)
- Weekly reading assignments needed to solve projects.
- First hour of each lab session may be used to discuss technicalities, address questions etc linked with projects.
- Detailed lecture notes, exercises, all programs presented, projects etc can be found at the Github address of the course.
- Computerlab: Most likely Fridays. We have reserved a time slot from 4pm to 8pm.
- Weekly plans and all other information are the github address of the course.
- Four projects, all have to be approved. The first project is pass/not passed only while the last three projects are graded and count 25% each of the final mark. The course ends with a final oral exam where you present a project of your choice. The final oral exam accounts for the remaining 25% of the final grade.

## Course Format

- Use version control like [Git](#) for repository and all your material.
- C/C++ is the default programming language, but Fortran2008 and Python are also used. All source codes discussed during the lectures can be found at the webpage and [github address](#) of the course. We recommend either C/C++, Fortran2008 or Python as languages.

## Topics covered in this course

- Numerical precision and intro to C++ programming
- Numerical derivation and integration
- Random numbers and Monte Carlo integration
- Monte Carlo methods in statistical physics
- Quantum Monte Carlo methods
- Linear algebra and eigenvalue problems
- Non-linear equations and roots of polynomials
- Ordinary differential equations
- Partial differential equations (may not be covered)
- Parallelization of codes
- High-performance computing aspects and optimization of codes

## Syllabus

### Linear algebra and eigenvalue problems, chapters 6 and 7.

- Know Gaussian elimination and LU decomposition
- How to solve linear equations
- How to obtain the inverse and the determinant of a real symmetric matrix
- Cholesky and tridiagonal matrix decomposition

## Syllabus

### Linear algebra and eigenvalue problems, chapters 6 and 7.

- Householder's tridiagonalization technique and finding eigenvalues based on this
- Jacobi's method for finding eigenvalues
- Singular value decomposition
- Cubic Spline interpolation

## Syllabus

**Numerical integration, standard methods and Monte Carlo methods (chapters 4 and 11).**

- Trapezoidal, rectangle and Simpson's rules
- Gaussian quadrature, emphasis on Legendre polynomials, but you need to know about other polynomials as well.
- Brute force Monte Carlo integration
- Random numbers (simplest algo, ran0) and probability distribution functions, expectation values
- Improved Monte Carlo integration and importance sampling.

## Syllabus

**Monte Carlo methods in physics (chapters 12, 13, and 14).**

- Random walks and Markov chains and relation with diffusion equation
- Metropolis algorithm, detailed balance and ergodicity
- Simple spin systems and phase transitions
- Variational Monte Carlo
- How to construct trial wave functions for quantum systems

## Syllabus

**Ordinary differential equations (chapters 8 and 9).**

- Euler's method and improved Euler's method, truncation errors
- Runge Kutta methods, 2nd and 4th order, truncation errors
- How to implement a second-order differential equation, both linear and non-linear. How to make your equations dimensionless.
- Boundary value problems, shooting and matching method (chap 9).

## Syllabus

### Partial differential equations, chapter 10.

- Set up diffusion, Poisson and wave equations up to 2 spatial dimensions and time
- Set up the mathematical model and algorithms for these equations, with boundary and initial conditions. Their stability conditions.
- Explicit, implicit and Crank-Nicolson schemes, and how to solve them. Remember that they result in triangular matrices.
- How to compute the Laplacian in Poisson's equation.
- How to solve the wave equation in one and two dimensions.

### Overarching aims of this course

- Develop a critical approach to all steps in a project, which methods are most relevant, which natural laws and physical processes are important. Sort out initial conditions and boundary conditions etc.
- This means to teach you structured scientific computing, learn to structure a project.
- A critical understanding of central mathematical algorithms and methods from numerical analysis. In particular their limits and stability criteria.
- Always try to find good checks of your codes (like solutions on closed form)
- To enable you to develop a critical view on the mathematical model and the physics.

### Additional learning outcomes

- has a thorough understanding of how computing is used to solve scientific problems
- knows some central algorithms used in science
- has knowledge of high-performance computing elements: memory usage, vectorization and parallel algorithms
- understands approximation errors and what can go wrong with algorithms
- has experience with programming in a compiled language (Fortran, C, C++)

- has experience with debugging software
- has experience with test frameworks and procedures
- can critically evaluate results and errors
- understands how to increase the efficiency of numerical algorithms and pertinent software
- understands tools to make science reproducible and has a sound ethical approach to scientific problems
- Is able to write a scientific report with software like Latex

## Computing knowledge

Our ideal about knowledge on computational science

Hopefully this is not what you will feel towards the end of the semester!



And, there is nothing like a code which gives correct results!!



- J. J. Barton and L. R. Nackman, \*Scientific and Engineering C++\*, Addison Wesley, 3rd edition 2000.
- B. Stoustrup, *The C++ programming language*, Pearson, 1997.
- An excellent text is [Discovering Modern C++](#)
- D. Yang, *C++ and Object-oriented Numeric Computing for Scientists and Engineers*, Springer 2000.
- And the [C++ resource network](#) provides great help.
- The [Fortran tutorial](#) is also very useful.
- And for Python programmers, see the textbook by [Hans Petter Langtangen](#)

## Extremely useful tools, strongly recommended

and discussed at the lab sessions.

- [Git](#) and a repository at [Github](#), this and next week (and later weeks as well).
- ipython notebook (Jupyter notebook, a great tool)
- [Qt Creator](#) as one possible IDE for editing and mastering computational projects (for C++ codes, see webpage of course), discussed during the whole semester. You can however use other IDEs as well such as [VisualC++](#).
- Armadillo as a useful numerical library for C++, highly recommended, discussed in connection with LinAlgebra lectures
- Unit tests, discussed throughout the whole semester
- Piazza for discussions and teaching material