First year in Physics at the University of Oslo

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Introduction and Motivation

Students of the Physics and Astronomy bachelor program as well as faculty at the department of Physics (DP) and Institute of Theoretical Astrophysics (ITA) have often remarked that there is a lack of Physics topics in the first year of study, and in particular during the first semester.

The setup of the first year of study is also essentially the same since the fall semester of 2003, when the Bologna process (Kvalitetsreformen) was introduced in Norway.

Moreover, during the last decade we have seen several changes in competences and skills of the incoming students as well as improved computational and experimental software and hardware. In addition, pedagogical research and technological innovations with respect to alternative ways of organizing lectures such as flipped classrooms and more, are all topics we believe should be reflected in the way we organize our bachelor program and higher education in Physics and Astronomy. With the center of excellence in higher education **Center for Computing in Science Education**, we have also the possibility to accompany pedagogical changes with ongoing and future research programs on university education.

We propose here a novel and new first year in Physics and Astronomy where the aim is to integrate theory, computations and experiments in a coherent way, including much of the same mathematical and computational aspects included in MAT-INF1100 and MEK1100 but now tailored to a Physics and Astronomy perspective, with a strong focus on an overarching understanding of the scientific method and its various elements from day one. We propose three new courses, with a great potential for pedagogical innovations and pedagogical research as well. These courses are integrated with central first year courses in Mathematics and Computing.

All three new courses include experiments which can be integrated with a numerical perspective using applications on smartphones and hardware like Arduino. A central benefit here is that students can carry out experiments at home or outside a standard lab environment. Furthermore, the integration of experiments with a programming perspectives allows students to carry out experiments and upload data to their computing devices (laptops/PCs/Tablets) for further analyses, interpretations and discussions. To strengthen the understanding of Physics being an experimental discipline we introduce also a new course on Statistics, Probability and Data Analysis for Physicists in the second semester. This course aims at a more coherent introduction of central elements from statistics needed in theoretical and experimental studies.

Present situation with description of courses, bachelor degree in Physics and Astronomy

All courses are scaled to ten ECTS (European Credit Transfer and Accumulation System).

First semester, Fall		
MAT 1100	MAT-INF1100	IN1900
Second semester, Spring		
MAT 1110	MEK1100	FYS-MEK1100

Present content (mainly learning outcomes)

Fall semester.

1. MAT1100

    - are familiar with the complex numbers and can calculate with them on Cartesian and polar form;
    - are familiar with the Completeness Principle for the real numbers and know how it is used in creating the theory of functions of one variable;
    - know how to define conituity, limits, derivatives, and integrals precisely, and can compute limits, derivatives, and integrals of functions of one variable;
    - are familiar with vectors and matrices and can use them for simple calculations;
    - know what functions of several variables are, can determine whether they are continuous and differentiable, and can compute and interpret directional derivatives and partial derivatives;

- can use the theory in the course to solve modeling problems, especially problems concerning integration, optimization, and related rates.

2. MAT-INF1100

    - are familiar with the basic properties of integer and real numbers, how they are represented in a * computer, and limitations of the representations;
    - can find formulas for the solution of some difference and differential equations;
    - are familiar with and can program numerical methods for approximate calculation of the derivative and the integral of general functions, as well as approximate solutions of equations, difference equations and differential equations;
    - are familiar with the general limitations of numerical methods discussed in the course and are able to estimate their errors using Taylor polynomials with remainder and the principles for representing real numbers in a computer;
    - can derive simple mathematical models for practical problems using derivatives, integrals and different kinds of equations;
    - are able to carry out proofs by induction, argue out simple, mathematical arguments, and present your reasoning in a clear and transparent way with suitable notation and terminology.

3. IN1900

    - be able to write programs that solve math problems you encounter in MAT-INF1100 – Modelling and Computations and MAT1100 – Calculus.
    - have basic skills in Python programming using data structures, functions, classes, objects, modules and vectorized calculations
    - be able to create program sketches and algorithms based on a mathematical specification of a science problem
    - be able to create solutions to minor real issues on a computer with user interaction, graphics (plot, animations) and storage/reading of data to/from disk
    - be able to use a variety of Python modules in self-interaction interaction to integrate, derive, find zeroes, calculate boundary values and sequences, and solve differential and differential equations from physics, biology and finance
    - be able to construct, find and correct errors in your own programs
    - be able to construct tests to verify that computer programs work properly

Spring semester.

1. MAT1110

    - can parametrize curves and surfaces and use these representations to create graphical figures and to compute arc length, line integrals and surface area;
    - know the definition of double and triple integrals, can calculate such integrals by means of different coordinate representations, and use them to solve practical problems;
    - can solve theoretical and practical optimization problems with and without constraints;
    - are familiar with the completeness property of Euclidean spaces, know how they form a foundation for numerical methods, and can write programs in MATLAB or Python to find zeros and fixed points of functions;
    - master Gauss elimination, are familiar with the concepts of linear independence and basis, and can find eigenvalues and eigenvectors and use them to analyze practical problems from both an analytical and a numerical perspective;
    - know what it means for a series to converge, can use tests to decide convergence and find domains of convergence, and can determine the Taylor series of a function;
    - can carry out simple mathematical arguments and computations and present them in a clear and coherent way with suitable notation and terminology.

2. MEK1100

    - have knowledge about scaling, the significance of physical units and dimensionless parameters;
    - can compute gradient and directional derivative, divergence and curl, equiscalar surfaces, field lines, curve integrals and circulation, surface integrals and flux, pressure force, particle derivative, in Cartesian and curvilinear coordinates, and have knowledge of the physical interpretation of these quantities;
    - can apply Gauss and Stokes theorems;
    - can apply potential and stream functions and have knowledge about potential flow;
    - can use the computer to visualize scalar and vector fields and to do numerical computations of fields;
    - have knowledge about the mass conservation equation and the equation of motion of fluids, Bernoulli´s equation for stationary ideal liquid flow, heat and temperature computations with convection and Fourier´s law.

3. FYS-MEK

   - be able to analyze forces that act on objects, apply Newton's laws to determine the equations of motion, and solve these both analytically and numerically,
   - be able to describe the rotational motion of rigid bodies using torque, moment of inertia, and angular momentum, and apply Newton's second law for rotational motion to solve the equations of motion,
   - be able to apply conservation laws for mechanical energy, momentum, and angular momentum to solve static and dynamic problems and to analyze collisions between bodies,
   - know the definitions that are relevant for elasticity theory,
   - be able to apply Lorentz transformations for position and velocity and explain length contraction and time dilation,
   - be able to apply different strategies to solve specific problems, introduce approximations if necessary, and interpret results and discuss these in a wider context.

Revised first year

The department of Mathematics is planning a revision of the content of MAT1100 and MAT1110. The most likely scenario is that the basic content will not deviate too much from the above. The learning otucomes of the programming course IN1900 are also expected to remain the same.

We think it is important that the DP and the ITA also perform a careful review and eventual revision of the scientific and pedagogical content of the bachelor program in Physics and Astronomy. In this conncetion we would like to advocate for a coherent first year in Physics and Astronomy where the aim is to integrate theory, computations and experiments in a coherent way, including much of the same mathematical and computational aspects included in MAT-INF1100 and MEK1100 but now tailored to a Physics and Astronomy perspective, with a strong focus on an overarching understanding of the scientific method and its various elements.

All three new courses will include experiments which can be integrated with a numerical perspective using applications on smartphones and kits like Arduino. A central benefit here is that students can carry out experiments at home or outside a standard lab environment. Furthermore, the integration of experiments with a programming perspectives allows students to carry out experiments and upload data to their computing devices (laptops/PCs/Tablets) for further analyses, interpretations and discussions.

To achieve this integration, we propose three new courses

1. FYS111X Mechanics and Modeling

2. FYS112X Classical Mechanics
3. FYS113X Statistics, probability and data analysis for physicists

The possible content is described below. The first year of study could then look like this if we aim at keeping courses of 10 ECTS. There is also the possibility to modularize these topics in units of 5 ECTS or 7.5 ECTS.

First semester, Fall		
MAT 1100	FYS111X Mechanics and Modeling	IN190
Second semester, Spring		
MAT 1110	FYS112X Classical Mechanics	FYS113X Statistics, probability a

Specific content of new courses

FYS111X Mechanics and Modeling. The Mechanics and Modeling course integrates central elements from MAT-INF1100 and FYS-MEK1100. The basic Mechanics content from FYS-MEK1100 is kept, that is we focus on elementary Newtonian mechanics and students will (optimally covered by chapters 1-13 of Malthe-Sørenssen)

- be able to analyze forces that act on objects, apply Newton's laws to determine the equations of motion, and solve these both analytically and numerically;
- be able to apply conservation laws for mechanical energy, momentum, and angular momentum to solve static and dynamic problems and to analyze collisions between bodies.

These concepts will be integrated with a computational approach where central algorithms for solving equations of motion of motion are introduced. This includes elements from MAT-INF1100 central to studies of differential equations and numerical solutions of integrals. To be more explicit this means that the students

- are familiar with the basic properties of integer and real numbers, how they are represented in a computer, and limitations of the representations;
- can find formulas for the solution of some difference and differential equations;
- are familiar with and can program numerical methods for approximate calculation of the derivative and the integral of general functions, as well as approximate solutions of equations, difference equations and differential equations;

- are familiar with the general limitations of numerical models for solving differential equations and integrals. Central methods for solving differential equations are the family of Euler- and modified Euler methods, the Velocity Verlet method and the family of Runge-Kutta methods. For integrals, standard Newton-Cotes quadrature methods like the midpoint rule, the Trapezoidal and Simpson's rule will be presented.
- can derive simple mathematical models for practical problems using derivatives, integrals and different kinds of equations;

In addition this course will include a set of selected simple experiments using the accelerometer on a standard smartphone. Students will then transfer the data to their own laptops/PCs/Tablets and perform a final analysis of the data such as calculating the velocity and the position based on the measured acceleration. The uncertainties with the measurements will be addressed in the second semester in the course FYS113X.

This course is integrated with IN1900 and MAT1100.

FYS112X Classical Mechanics. This course is a continuation of FYS111X and includes more advanced topics tailored explicitely to Physics and Astronomy students. The integration of central theoretical, computational and experimental elements as well as a coordination with FYS113X and MAT1110 plays an important role. In addition to more advanced topics in mechanics not discussed in FYS-MEK1100, this course includes elements from MEK1100.

Possible topics are

- Repetition of central elements from FYS111X, Newton's laws, conservation laws and solutions of equations of motion, analytically and numerically
- Variational and Lagrangian Calculus with examples and derivation of equations of motion
- Two-body problems and central forces, Kepler's laws, Gravitational problems, classical two-body scattering
- Oscillations, Driven and damped oscillations, coupled oscillations and Fourier series. Numerical and analytical solutions of equations of motion.
- Mechanics and Equations of motion in non-inertial frames, accelerating and rotating frames, Coriolis and Centrifugal forces. Numerical and analytical solutions of equations of motion.
- Rigid body kinematics and Dynamics. Numerical and analytical solutions of equations of motion.
- Special Relativity
- Tentative (could also be deferred to FYS3120) Hamilton's principle and Hamiltonian mechanics. Understanding important symplectic differential equations and energy conservation.

- Basic elements from fluid mechanics, mass conservation equation and the equation of motion of fluids, Bernoulli´s equation for stationary ideal liquid flow, heat and temperature computations with convection and Fourier´s law.
- Knowledge of scaling, the significance of physical units and dimensionless parameters
- Gradient and directional derivative, divergence and curl, equiscalar surfaces, field lines, curve integrals and circulation, surface integrals and flux, pressure force, particle derivative, in Cartesian and curvilinear coordinates, and have knowledge of the physical interpretation of these quantities
- Basic understanding of Gauss and Stokes theorems in mechanics examples
- can use the computer to visualize scalar and vector fields and to do numerical computations of fields
- **Discuss which experiments to include**! See also next course.

FYS113X Statistics, probability and data analysis for physicists. These topics have normally been taught in a scattered way in different courses. This means that the students are never exposed to a coherent view on central elements of probability theory, statistics and data analysis. The results is often a lack of understanding of central elements in the analysis of experimental and theoretical data. The aim here is to establish such a course, integrating the needed statistical theory with computations and analysis of theoretical simulations and experimental results. Moreover, it allows us to focus on central aspects of data analysis with emphasis on physics and astronomy and simpler machine learning algorithms. Central topics are

1. Basic concepts
   - Randomness and probability, basic principles
   - Distributions, moments and errors. Central concepts like moments, errors and essential distributions (Gaussian, Binomial, Poisson, uniform, exponential, log-normal etc), central limit theorem
2. Distributions in the physical world
   - Distributions in the physical world, examples from different types of experiments
   - Confidence intervals
   - Statistics with binomial, Poisson and Gaussian distributions
   - Random processes and distributions arising from these
   - Random numbers and Monte Carlo methods

3. Probabilistic inference
    - Hypothesis testing and Bayesian approach to probability
    - Parameter estimation
    - Correlation testing and covariance
    - Computations and model fitting

4. Frequentist inference and simple Machine Learning algorithms
    - Linear and Logistic regression, regression and classification problems
    - Decision trees and Random forests
    - Simple Neural networks

Need to discuss which experiments we can do that can be integrated with FYS113X. A dedicated workshop which addresses possible experiments in FYS111X, FYS112X and FYS113X is planned for fall (late) 2020.

Coordination with other programs

The course FYS-MEK1100 has also served as a recommened or compulsory course in other bacheloer of science programs. These are the

1. Electronics, informatics and Technology, fourth semester
2. Geophysics and Climate, second semestero Geology and Geography, second semester o Mathematics and Physics, fourth semester
3. Mechanics and technology, fourth semester
4. Materials science, second semester
5. Educational Master program (Lektorprogrammet).

An alternative here is that the new course FYS111X is offered both during the fall and during the spring semester. Physics and Astronomy students will follow the fall variant while the other educational programs are offered the spring variant. FYS111X has to a large extent many of the same central elements included in FYS-MEK1100.

A careful revision may however be needed in order to accomodate the needs of these other programs.

Education Research and Innovation

What is presented above aims at innovating the way we teach physics, integrating concepts and topics normally scattered across many different (and often disconnected) university courses and opening up also for innovative approaches to university education and studies.

The overarching motivation is to allow for a deeper understanding of the scientific method at an earlier stage in our education by integrating theory, experiments and computations. This has the potential to elucidate essential stages of the scientific process.

There are several other interesting aspects which can define new educational research projects, in particular an integration of flipper classrooms that normally allow for a tighter connection between students and teachers (faculty, learning assistants and teaching assistants).

Exploring flipped classrooms may involve the development of new digital learning material of high quality, such as videos, podcasts and improved learning material. This could also include developing or adapting curricula and learning objectives that are meaningful in online settings.

Integrating thus the introduction of a new first year for the Physics and Astronomy program with existing and planned research in close collaboration with the Center for Computing in Science Education has the potential to improve considerably the quality of our education. At present, there are no Physics undergraduate programs (to our knowledge) which integrate from day one theory, computations and experiments. As such, this proposal brings the Computing in Science Education initiative (which started with the reform in 2003) to a higher and new level.