

Python-based Lagrange analytical mechanics course

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Software

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Summary

We present a code-based undergraduate course on analytical mechanics for engineering students with little to no prior programming knowledge. This 16-week flipped classroom (?) course provides skills to calculate dynamics and strains of simple mechanical devices, modelled as rigid bodies by solving Euler-Lagrange equations. Each example and practice exercise is solved using computer-based analytical and numerical calculations focusing students' attention on physics modelling and not on repetitive mathematical tasks. This approach also aims to improve creativity, the students have to solve problems by trial and error ([Hoffmann et al., 2021](#)).

The course addresses specific regional issues faced by third-year Latin American students (mid-career), that by then have learned how to solve ordinary differential equations. Theory and examples exercises, along with the *Python* code that solves them are presented in *Jupyter notebooks* run online to avoid installation and hardware requirement issues. Currently, the material is available in a GitHub repository in Spanish and has only been partially translated into English.

Statement of need

Latin American public universities face two simultaneous constraints: tight budgets and the need to accommodate their classes' schedules to day-working students ([Vallejo et al., 2022](#)). These cash-stripped universities seldom avail computing resources for courses that are not directly related to computer science or programming. Also, as undergraduate programs on engineering at Latin American universities are usually longer than the three-year bachelor's degrees at their Anglo-Saxon counterparts, it is quite common for students to already be part of the labour market while studying. As a result, they have tight schedules and are often unable to attend to university during daytime hours.

The course presented addresses those issues by providing a free, online, and asynchronous learning environment allowing students to study at their own pace through the flipped classroom approach ([Moraros et al., 2015](#)). In advance to weekly meetings, students are required to study the theory and examples provided in the notebooks, as well as to initiate solving the accompanying exercises. During those evening meetings, whether online or in person, students are encouraged to ask questions and discuss the problems they could not solve with the teaching staff.

Basis for the syllabus

Traditionally, systems addressed in analytical mechanics courses are kept as simple as possible, to limit the extent of the mathematical work required. So, modelling of multiple machine parts is seldom undertaken, as that would lead to a level of complexity sometimes

42 untenable for students and teaching staff working on the blackboard or paper. This course
43 aims to avoid this pitfall by taking advantage of the relative simple syntax of modern
44 programming languages to tackle mathematical problems. In this way it is possible to
45 rapidly introduce life-like problems avoiding oversimplifications to the students.

46 The required modelling as well as algebraic and calculus operations to generate the
47 Euler-Lagrange differential equations are performed using *physics.mechanics*, the symbolic
48 dynamics sub-package of the *SymPy* library (Meurer et al., 2017). Its code was ported
49 from the *PyDy* library, a replacement of *Autolev* (Levinson & Kane, 1990), a commercial
50 software that instrumentalised the Kane's method (Kane & Levinson, 1985). As stated in
51 the online textbook for the *Multibody Dynamics course at TU Delft*, a successor to the one
52 *PyDy* was developed for, this method avoids accounting for non-conservative forces with
53 Lagrange's multipliers, but it requires modelling forces in the system (Jason K. Moore,
54 2024). Our choice was instead to make students model systems solely by their energy,
55 a more traditional approach, in order to immerse them into a radically different way of
56 solving mechanical problems in their first contact with analytical mechanics. We think
57 that when facing problems requiring a more efficient method, they will be able to apply
58 such other less abstract methods.

59 Although *physics.mechanics* provides functionality for deriving equations of motion using
60 *Lagrange's method*, this course aims for the student to follow the standard mathematical
61 notation and procedures, as they would have done on paper. The idea is to ensure that
62 students can verify each step of the process and only later rely on functions built around
63 these steps, avoiding any *black box*.

64 We would like to emphasise that the course is not about teaching programming, nor about
65 high-performance modelling of mechanical systems. The aim of employing the computer is
66 to free-up students from the repetitive nature of the calculations, so they can focus on the
67 physical aspects of the problems. The deliberate decision that everything get solved by
68 code, even the earliest examples, aims to reinforce the advice given to students to avoid
69 solving the initial problem sets on paper. Some students did so at earlier editions of the
70 course, only to get stuck later while solving more complex problems without the computer
71 help. By slight modifications over the Python code presented by the teaching staff, students
72 build their own library of solutions to address mechanical modelling challenges. Once the
73 students generate the Euler-Lagrange equations, their numerical solutions are obtained
74 using the *Scipy* library (Virtanen et al., 2020), and plotted using *Matplotlib* (Hunter, 2007)
75 to better understand the physical implications of the solutions.

76 Overview, Content, and Structure

77 Full course material is available in a GitHub repository in *Spanish*, with an ongoing
78 *translation to English*. The first twelve folders contain the course material, each one corre-
79 sponding to a unit: 1. Course methodology, Newtonian physics and Sympy introduction.
80 2. Degrees of freedom, generalized coordinates and energy. 3. Euler-Lagrange mechanics,
81 Euler-Lagrange equations. 4. Constraints as a function of coordinates. 5. Numerical
82 solving of Euler-Lagrange equations. 6. Constraint reactions and Lagrange multipliers.
83 7. Non-conservative forces in the Euler-Lagrange framework. 8. Rigid-body and inertia
84 tensor. 9. Rigid-body, Euler equations. 10. Oscillations in single degree of freedom (SDoF)
85 systems, forced oscillations and discrete systems. 11. Oscillations multiple degrees of
86 freedom (MDoF) systems. Normal modes of discrete systems.

87 Each folder contains Jupyter notebooks with the required theory for the unit subject
88 alongside the code that solves example exercises. The students only need to modify
89 that code to solve the exercises proposed at the accompanying problem sets. It is worth
90 mentioning that many problems are modifications of problems presented in the course
91 bibliography, and that they are cited, to help the students follow possible issues and to
92 induce them to further use the textbooks. The problem sets are provided in PDF format

93 alongside their LaTeX source and figure files, allowing their customisation. The number of
94 exercises in each problem set, while still being illustrative of the variety of the unit subject
95 applications, is kept small in order to make their solving mandatory on a weekly basis.
96 Those of units 8, 9 and 11 are exceptions, requiring two weeks each, as they deal with
97 subjects that had shown to be somewhat more demanding to students.

98 Two further weeks complete a 16-week schedule. These are reserved not only for the
99 students to submit overdue exercises but, mainly, to perform an oral presentation on how
100 they solved a final project. Its aim is to calculate torques and forces that the motors of a
101 simplified factory robotic arm should apply to make it perform a sequence of movements.
102 As it requires the student to master the skills acquired during the first nine units, its
103 statement is presented at the second week for that unit. This arrangement gives enough
104 time for the students to consult on its difficulties and prepare the presentation. The oral
105 examination is intended to gauge the students' learning, not only on the physics and
106 computational skill required to solve this kind of problems, but also on how to provide a
107 well planned oral presentation.

108 Implementation

109 The *Google Colaboratory* service allows students to read and execute Jupyter notebooks,
110 as it currently demands no payment and can be accessed from any internet browser.
111 At UNLaM, the university where the course is taught, *SageMaker StudioLab*, *GitHub*
112 *Codespaces*, *Cocalc* or indeed *Kaggle* had also been tested for this purpose. Nevertheless,
113 Colab, as it is commonly known, is currently used because it provides a useful feature
114 for students to pose questions via side-notes to each cell of the notebooks. Teaching staff
115 can reply them individually, and students can re-reply, thus providing an asynchronous
116 interaction channel in between the weekly synchronic meetings.

117 Students are required to submit their solution to the complete course's problem sets. *MS*
118 *Teams* is used to assign and keep track of student's work, but any LMS, such as the open
119 source *Moodle*, can fulfil this task. Teaching staff check the submissions and, if required,
120 returns them with comments to correct them. This way, students are encouraged to solve
121 all exercises, as they are mandatory to pass the course, and to ask for help when they are
122 stuck.

123 Conclusions

124 The mechanical engineering programme is relatively new at UNLaM, so the number of
125 students per class is still low, around eight, thus allowing personalised tracking of student's
126 progress. Larger audiences will provide a challenge, probably requiring to include new
127 teaching assistants as well as introducing automatic grading, to somewhat keep the current
128 methodology.

129 For the time being, feedback from students consistently indicates a high level of satisfaction
130 with this course, especially with its code-driven aspect. Additionally, students express
131 interest in the final examination as it provides an opportunity to apply both their presen-
132 tation skills and the knowledge acquired throughout the course. In relation to the flipped
133 classroom model, students acknowledge that it requires a grater effort, but a majority of
134 them agree that it is a positive and beneficial implementation. This is in line with previous
135 research on the flipped classroom model for advances mechanical engineering courses (?).

136 The authors are confident that the methodology employed in this course offers greater
137 practical utility to students in subsequent subjects and their professional lives, surpassing
138 the benefits of a traditional course.

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