BIO-INSPIRED MATERIALS & TECHNOLOGIES:

A pathway towards sustainability

  

Aim of the course: Equip students with the ability to analyze, model, and design systems and technologies inspired by biological structures and processes, with a focus on sustainable innovation.

Student duty:

Students are expected to attend the lectures and develop their own project idea. It is recommended that they identify a potential technological challenge in advance and explore possible bio-inspired solutions. During the practical sessions, the course organizer will assist students in refining their ideas and arguments. When applicable, students are also encouraged to choose a challenge that aligns with their own research interests.

Independent study and/or experimental work may be required to support their project.

Target audience: PhD students of any scientific or technological area.

Max participants: 20.

Course organizer:

Gabriele Greco received his bachelor and master degree in physics from the University of Ferrara and his Ph.D. in mechanical engineering from the University of Trento. He is currently a post-doctoral researcher at the University of Pavia and his research interests focus on the mechanics of biological materials such as pericardium, spider silk, and artificial silk structures. His passion for spiders led him to co-found the Italian Society of Arachnology - Aracnofilia, in which he serves as vice president.

To register send an email to gabriele.greco@unipv.it

Course learning outcomes/abstract

The course will equip students with the skills to analyze, model, and design systems and technologies inspired by biological structures and processes, with a particular focus on sustainable innovation.

The frontal lectures will introduce the fundamental principles of bio-inspired design: why we learn from nature and how to approach biological systems critically, avoiding common misconceptions. We will examine best practices, highlight frequent pitfalls, and conclude with an overview of key biological phenomena and materials that have inspired technological innovation — from sustainable forest management to the development of high-performance materials.

During the interactive and practical sessions, students will apply these concepts to their own PhD research projects (preferred) or to a project assigned by the instructor. Each student will be invited to identify a specific technological or societal challenge within their research that could be addressed by drawing inspiration from a natural process or material. Alternatively, they may choose a challenge that could be solved by applying principles derived from their own research.

Based on the selected problem, students will develop a concise presentation proposing an evidence-based solution to the chosen challenge. The supporting evidence may be generated through experiments, literature review, or analytical work carried out independently. For experimental activities, students may be organized into small groups as appropriate.

Goals:

1) Enable students to independently identify interdisciplinary approaches for addressing complex problems.
2) Encourage students to leverage their own skill sets to foster cross-disciplinary knowledge exchange.
3) Equip students with relevant examples illustrating how sustainable innovations can emerge from inspiration drawn from biological systems.

Number of hours and planning

The course will consist of a total of 20 hours, divided into two main phases: 10 hours of frontal lectures and 10 hours of laboratory or group activities. At the end of the course, a final presentation session (exam) will serve as a “return phase,” during which students will present their projects. The date of this session will be agreed upon together with the students.

During the first 10 hours of lectures, the following thematic areas will be explored (with final topics adapted to the interests and backgrounds of the enrolled students):

1. <u>Bio-Inspired Design and its Practices: Making Innovation Sustainable.</u> This introductory lecture will cover the fundamental principles of bio-inspired design: why we learn from nature, and how to approach biological systems without falling into common misconceptions. We will explore best practices, frequent pitfalls, and conclude with an overview of key biological materials such as silk, nacre, bone, collagen, and wood.

2. <u>Mechanical Characterization of Biological Materials.</u> Students will be introduced to the main techniques for characterizing biological materials. The lecture begins with morphological analysis, comparing the strengths and limitations of microscopy techniques like SEM, AFM, and light microscopy. We will then focus on mechanical testing methods, including tensile and compression tests, and their challenges, along with advanced techniques like AFM-based and custom-built devices for nanoindentation studies.

3. <u>Bio-Inspired Adhesion Phenomena.</u> This lecture will first provide basic knowledge related to adhesion phenomena, such as capillary adhesion or peeling theory. Then, the lecture will explores biological adhesion and how nature solves complex adhesion challenges. Examples include underwater adhesion in octopuses, diving bell spiders, and mussels, as well as dry, reversible adhesion seen in geckos and spiders.

4. Bio-Inspired Structures for Vibration Attenuation and Sound Control. Focusing on dynamic responses in nature, we will examine how organisms have evolved to manage sound and vibration. Notable cases include the woodpecker's brain and its resistance to deceleration forces, and moths that absorb ultrasound through unique scale structures. These insights will be linked to the design of acoustic metamaterials.

5. Bio-Inspired Textiles and Fibrous Materials. This lecture addresses the need for sustainable, high-performance fibers. Nature provides numerous examples such as silk, wool, and hemp, which offer viable alternatives to synthetic, petroleum-based materials. Their mechanical and ecological advantages will be discussed in the context of textile innovation.

6. Bio-Inspired Soft Robotics. An introduction to soft robotics, a rapidly growing field that leverages compliant materials for actuation rather than rigid components. Inspired by organisms like octopuses and plants, soft robots are revolutionizing areas such as biomedical engineering. Key design principles and application cases will be covered.

7. Bio-Inspired Mechanical Sensors and Responsive Systems. This lecture will explore how natural organisms sense and respond to their environment, focusing on mechanical sensors such as slit sensilla in arthropods and hair-like structures. We will examine how these biological systems inspire innovative sensing technologies.

8. Structure–Function Relationships in Natural Materials. Understanding the link between structure and function is critical in material design. We will explore this relationship through examples like silk and collagen, using theoretical models developed by Termonia and Buehler to describe how hierarchical organization governs mechanical performance. The lecture will show the major benefits and limitations of these models, providing a pathway for delivering more precise predictions.

9. Bio-Inspired Hydrophobicity and Wettability. This lecture will examine the biological control of surface wetting properties. In this sense, basic knowledge about surface wettability will be provided. Hydrophobicity is vital for applications such as anti-icing coatings, while controlled wettability can aid water harvesting in arid environments. Case studies include the super hydrophobicity of lotus leaves and the water collecting desert beetle cuticle that achieve such performances by employing only structural features.

10. Bio-Inspired Biomaterials. We will conclude the series of lectures with a focus on bio-inspired manufacturing strategies. Concepts such as self-assembly, additive manufacturing, and bio-composites will be revisited through the lens of natural processes, highlighting how nature's paradigms can inform sustainable production.

Period: winter semester, preferably November/December

Evaluation criteria:

Each student will develop and present a case study of their choice—either a bio-inspired prototype or conceptual design—integrating the principles learned throughout the course. Presentations will be delivered in PowerPoint format (PPT).

To support this activity, students will have access to laboratory facilities and supervision, if needed.

Evaluation will be based on the student's ability to deliver a logically structured, evidence-based presentation that effectively demonstrates their understanding of bio-inspired design and the application of course concepts to their project.