Teaching cross-disciplinarity in the natural sciences: A case for natural philosophy

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Abstract

Interdisciplinarity in the natural sciences is a phrase one regularly hears in the context of teaching and learning, at all levels of study, from the classroom to the research environment. But what do we really understand from this term? In most cases, from the perspectives of the physical and life sciences, it is used to describe the overlap of chemistry and materials science, molecular biology and genetics, or biochemistry and biophysics, for example. While these interconnections across different fields broaden the horizon of the student, they do not always allow them to situate their learning in a broader societal context.

The natural sciences have the potential to solve many problems facing the future of our planet and these solutions come from interdisciplinary research. However, creating solutions is only part of the story. As scientists we also need to understand how to exploit our ideas, whether they should be exploited at all, and how our research fits into the world around us. To ensure future generations of scientists can both understand and solve the problems in the world around them, we need to broaden the concept of interdisciplinarity in teaching and learning. We argue that science teaching and learning must include cross-disciplinary interactions, that is, teaching a subject from the perspective of another subject, such as philosophy, or adopt different scientific philosophies to ensure the innovators of tomorrow can make well-balanced choices about the impact of their discoveries on communities and societies at large.

This approach of cross-disciplinarity is not without challenges. Integrating humanities modules with science modules in the curriculum will be beneficial, as it will introduce cross-disciplinary perspectives into teaching in the natural sciences from the bottom up. This encourages us, as teachers, to view our subjects in a more philosophical manner, and impart this deeper perspective and understanding on our students. With a specific focus on the teaching of chemistry and its cognates, subjects that have less of a modern tradition of conceptual thinking, we provide literature arguments supporting the case for philosophy in science, perspectives on how to address cross-disciplinarity in chemistry teaching, and some classroom activity suggestions to support cross-disciplinary learning.

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Introduction

Although the PhD has only been awarded since the early 19th century (Bourner, Bowden and Laing, 2001), it reflects the notion that scientific investigation was considered as natural philosophy and scientists as natural philosophers, following the style of the Platonic Academy (Figure 1). Natural philosophy was characterized by rigorous scientific investigation and robust scientific argumentation, the cross-over between the analytical nature of the sciences and the critical thinking of philosophy (Laplane, *et al.*, 2019). However, through the process of increasing specialization, these two domains became unentangled and began to follow independent trajectories (Gare, 2018). Today, the students we teach will become Bachelors or Masters of Science, reflecting the deep practice-oriented understanding of the field of natural science but with less focus on critical thinking and cross-disciplinary perspectives.

Figure 1: The Platonic Academy Mosaic, Villa T. Siminius Stephanus, Pompeii. Unknown author, Public Domain, Wikimedia Commons

Teaching in chemistry is highly specialized, focused on a deep practical understanding of the way chemical and biological systems behave, mastery of experimental techniques, and innovation in terms of analysis and materials design (Mulder, 2012). However, scientists spend less time questioning why these studies are important, what knowledge is gained from these investigations and what the implication of this knowledge is, both for ourselves and in a wider context (Erduran, 2013). By critically evaluating the materials that are taught to students, it is hoped that they will be better placed to encounter and react to the challenges they will face after they graduate and become practicing scientists. Let us be clear, the challenges chemistry faces today, and will continue to face in the future, are immense. The climate crisis, food and energy security, public health crises, environmental degradation, and innovations in health and biomedical sciences that come with significant ethical considerations, are major issues that cannot be addressed from a natural sciences perspective alone (Schlögl, 2010; Cole, *et al.*, 2018; Schwarzman & Buckley, 2019; World Economic Forum, 2021). Students, already from the undergraduate level, must have the capacity to critically reflect on innovations and their implications before forging a path ahead (Andreoletti & Maugeri, 2019). They must also be provided with the skills to present logical arguments for their thoughts on the subject matter and recognize good and bad reasoning when presented with scientific treatises (publications, theses, *etc.*) (Lévy & Erden, 2020). The focus today lies primarily in interdisciplinary teaching, *i.e.,* merging two fields to create new research areas (Mulder, 2012), and not on cross-disciplinary methods, *i.e.*, viewing one field from the perspective of another (Nicolini, Mengis & Swan, 2012). While interdisciplinarity is extremely valuable, it is the combination of interdisciplinarity and cross-disciplinarity approaches, referred to in the past as natural philosophy, that has the greatest chance of producing creative, critical thinkers ready for the challenges that science practice will face in the future (Park, Leahy & Funk, 2023; Meso, 2023).

Thankfully, we, the authors, are not alone in this wish to integrate a more philosophical approach to science teaching. A large number of recent articles highlight the value and advantages of bringing philosophy and natural science synergisms together (Ankeny, *et al.*, 2011; Gare, 2018; Laplane, *et al.*, 2019; Lévy & Erden, 2020; Momennejad, *et al.*, 2021). These articles highlight innovations that have come about from the cross-over between the two fields.

They propose many methods to re-integrate philosophers and scientists, and while we agree with their proposals, such as hosting philosophers in science laboratories, making space for philosophers in scientific conferences and vice-versa and co-supervising research students, we believe reintroducing philosophical methods into science teaching is the first step that needs to occur on this path to better integration of the two fields.

Through our interactions within the context of the *Fundamentals of Teaching and Learning Programme* at the ETH, the authors, one coming from the chemical sciences and one from the biological and food sciences, were introduced to each other's ideas about the place of natural philosophy in the chemical and biological sciences and decided to explore these ideas further. In this paper we introduce the concept of natural philosophy and the benefits of introducing a philosophical teaching approach in the chemistry and biology classroom. We follow this with suggestions of several learning activities that invite students to develop natural philosophical perspectives. These activities are designed to encourage students to examine their course matter using three fundamental questions grounded in philosophy (Marshall, 1973):

1. *Why are we interested in this system in the first place*?
   (Epistemology and metaphysics – the nature and scope of knowledge)
2. *Why is this system important?*
   (Logic – good and bad reasoning)
3. *What are the implications of this knowledge in a wider context?*
   (Ethics – is this the right or the wrong action to take?).

By encouraging students to reflect on course matter in this way, we are aiming to provide a grounding in natural philosophy from the bottom up. These questions translate into specific skills that students can practice with these activities, in particular, the ability to confront and criticize the *status quo* (*i.e.*, reflection and critical thinking) and the initiative to ask more conceptual questions (*i.e.*, curiosity and inquisitiveness). The following section provides the literature argument for natural philosophy, which leads into a description of the classroom activities, finishing with an analysis of the intended outcomes of the classroom activity with respect to the literature.

Examples of institutional approaches to Natural Philosophy

Many educational institutions have already recognized the value of introducing natural scientists to courses in philosophy, logic, and ethics. At ETH Zurich, for example, humanities courses are obligatory for students in the natural sciences; however, these courses run alongside natural science courses, following a more inter-disciplinary style of teaching. Students themselves are required to make the link between the two fields. We argue that students require first a grounding in the basics of both fields and then instruction on how to view each field from the perspective of the other, in a cross-disciplinary manner. Unless students practice applying philosophical skills in their chosen discipline throughout their entire academic career, these essential critical skills will be lost. At ETH Zurich, for example, ethics is not taught to undergraduate students taking the Interdisciplinary Studies or Physics courses. For food science and chemistry, the authors' own disciplines, ethics is barely introduced to students.

We propose that natural philosophy be integrated into regular science classes to maintain and further develop critical thinking, logic, and ethics skills. This is in line with the liberal arts-based education system, common in the United States and other countries with educational systems modelled on the US system, such as the Philippines. At the University of the Philippines, for example, there is a "general education" program, which is similar to the liberal arts program. The purpose of the general education program is for students to learn topics from other courses that they would not have taken if a strict "major-only courses" is followed. For example, a communication arts student will take a general mathematics course or a mathematics student will take general arts and literature courses. In addition, philosophy courses are also part of the general education electives. This way, students are provided with a well-rounded curriculum. This encourages creativity and interdisciplinary thinking, and equips students with skills that will make them more competitive in today's digital-based world and work culture.

To this end, the following two sections comprise a selection of active learning sequences that will help educators promote philosophical thinking in the chemistry classroom as a step towards, or a complement to, philosophical thinking across the educational spectrum. These active learning sequences can be integrated during introductory classes at the start of the courses so that there will not be any trade-offs with other content in the curriculum.

Classroom learning activities promoting Natural Philosophy

Part I: Introducing the active learning sequences

In this section we present some simple activities to use in the classroom, known as active learning sequences, that could be beneficial to other educators when incorporating these approaches for the first time. These sequences are designed to introduce critical thinking, logic and the implications of knowledge to the chemistry classroom, and build in complexity to allow students to probe their learning more deeply.

Sequence 1: Abstract thinking

Competences: Introducing critical/abstract thinking, logic and reasoning

This activity was derived from a common mathematical problem known as Barbier's theorem (related to curves of constant width) and how that influences the design of manhole covers (Chamberland, 2016) and expanded into a critical thinking exercise in the General Education program of the University of the Philippines. We have summarized the exercise here to introduce students to abstract thinking and reasoning.

This activity seeks to use general information that the student has at their disposal (the appearance of different shapes, orientations of familiar objects in the cityscape) to begin to reflect on the decisions we make as scientists and how we must evaluate these decisions under a number of parameters before deciding whether this is an appropriate process or line of investigation.

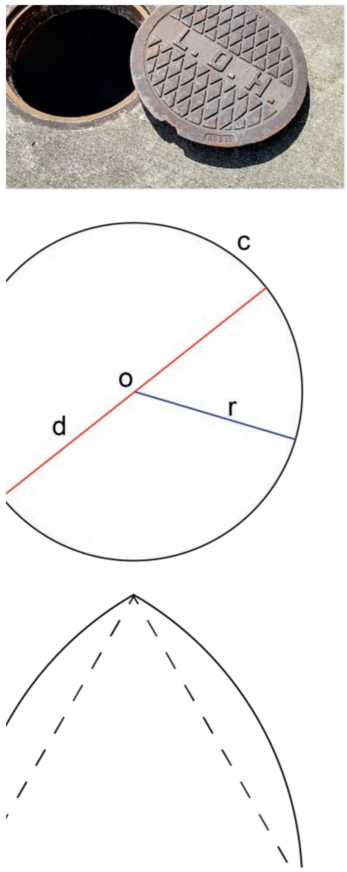

Figure 2: Manhole cover © Wikimedia Commons, CC 2.0 License (a) with examples of geometric shapes having a constant width: circle (b) and a Reuleaux triangle (c). d = diameter; o = origin; r = radius and c = circumference

For this task students are introduced to the manhole cover problem. (Chamberland, 2016) Students may question: "where will I apply geometry in everyday life?" They are then asked to reflect on a manhole cover. Why do they think the manhole cover is circular? Geometry tells us that as a curve of constant width, the cover will not fall in the hole (Figure 2a, b). Students are then asked to think about other shapes that would also not fall? In fact, any curve of constant width, *i.e.,* a Reuleaux triangle, or a rounded edge triangle, would not fall (Figure 2c). Thus, the students must also consider the implications of using a triangular cover instead of a round one in terms of cost, accessibility, and manufacturing? What other implications exist if the manhole cover can fall easily?

Sequence 2: Speculating about purpose

Competences: Logic and reasoning, creative thinking, abstract thinking

This active learning sequence is derived from the general aptitude tests many students encounter in high school, which are based on J.P. Guildford's divergent thinking test (also known as the alternative use test). Developed in the 1960s, this is still considered an excellent measure of creative or divergent thinking aptitude (Runco and Acar, 2012). We aim to employ it here to familiarize students with the concept of divergent thinking and speculating on the purpose of a standard object. Students are asked to list all the things they can do with a common laboratory object, *e.g.*, a weigh boat, in a fixed period of time (Figure 3). Students should be given a short period of time (5-10 mins) to list other uses, followed by a short group discussion where they discuss their list. This is a good warm-up exercise for activity 3, as it does not require subject-specific knowledge. Students will commonly be able to come up with 10-15 ideas in approximately 10 minutes, although there is no upper cap on the number of ideas! A further 10 mins can be reserved for reasoning in small groups. This could then be followed by a comparison between groups if time allows.

Figure 3: Potential uses of a standard plastic weigh boat. Image created with BioRender

Sequence 3: Rethinking the status quo

Competences: Subject specific abstract reasoning, conceptual thinking, divergent thinking, logic

Building on from sequence 2, we can combine the skills of the first two activities and expand them in a subject specific direction. This active learning sequence is designed to encourage students to think specifically about why we use certain chemical processes or materials and what other things in the world around us carry out the same functions, and could potentially replace the *status quo*. It allows students to evaluate common materials, how they function, where they are used and what other things do this, with a deeper subject specific focus. Ultimately, it should allow students to envision new ways of achieving the same end goal, that are perhaps more sustainable or economical. In the first stage, students are shown a picture of a common product or material, for example, superglue (Figure 4), with a series of questions on which to reflect.

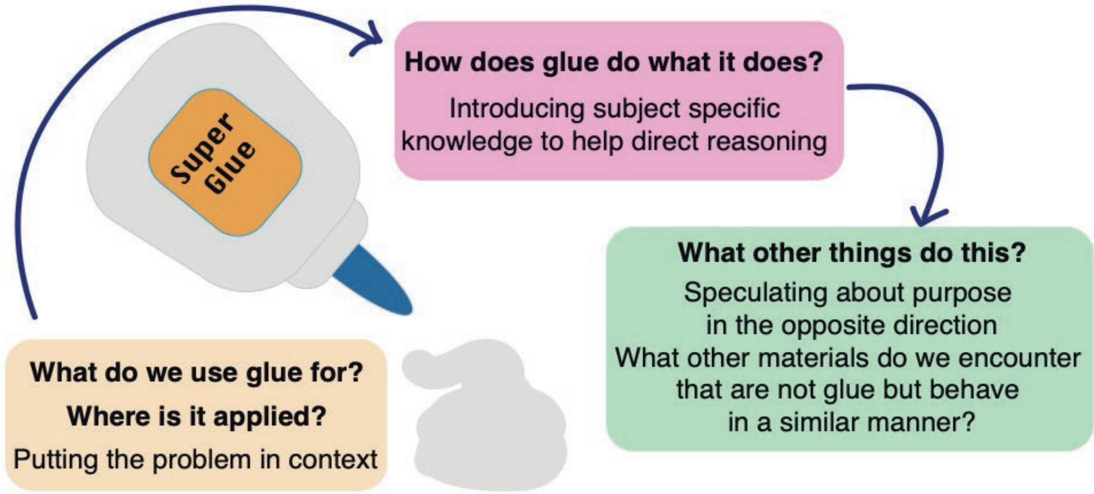

Figure 4: Impulse slide for active learning sequence 3, showing a graphic illustration of superglue with a series of questions for reflection, along with the purpose of these questions.

Students, in small groups, should reflect on the functions of the item using the orange and pink highlighted questions in Figure 4. Ideally, the instructor should provide the students with an interactive tool on which to record their answers. There are a number of different tools available for this with varying degrees of complexity (for setup) and anonymity (for participants) that must be assessed on a class-by-class basis, *e.g.*, Google Slides, Padlet or Mentimeter (Google, 2006; Goel & Piyush, 2012; Warström, 2014). This activity is designed to connect the thought processes exercised in Sequence 1 and 2. Glue is a common household item, but what does it do? and what are the external (economic, social, environmental) considerations that contributed to defining the processes we currently use to produce and use it. This is building on Sequence 1, abstract thinking and reasoning. Building on sequence 2, speculating about purpose, now we aim to fix the purpose but understand how many other ways we can achieve it. This also promotes creativity by encouraging students to reflect on all the sticky substances that are produced in nature to create a list of potential candidates. The students then return to the reason skills from Sequence 1 to understand the plausibility of replacing glue with any of the materials on their list. Essentially, this Sequence moves back and forth through the skills learned in Sequence 1 and 2 to reinforce the students learning.

Part II: Analysis of learning activities promoting Natural Philosophy

Sequence 1 is intended as an ice-breaker to introduce the student to critical reflection in the science classroom. The desired outcome here is that the student begins to question the reasoning behind common items in their everyday life and to understand that specific decisions and processes were employed to create that item and bring it into everyday use. This allows the students to gain some insight into the reasoning behind process development, which they can then transition to thinking about chemical processes in the same manner later.

Sequence 2 builds on Sequence 1 to take the student in a more specific direction, in their field of study, essentially exploring the applications of a mundane object, like a weigh boat, in non-standard applications in their field of study. In part 1 of this exercise, we are aiming to encourage students to explore their creativity, by thinking of non-standard applications for common items. In part 2 students exercise logical reasoning, as they must convince their group that this is a reasonable use for such an object. By comparing between groups, students are also given the opportunity to question the logic of their peers, a useful tool in critical thinking.

Finally in Sequence 3 we can build on the success of sequence 2. Students have been primed for out-of-the-box thinking. Questions 1-3 are for warming up, there are relatively few answers at this point because the mind is focusing on one thing and what it does. Now we can ask the students to reflect on the pros and cons of the item: Why is glue useful? What are the major issues with glue? Answers should now start to open up, there are really no right or wrong answers here, as in the previous activity, as long as they can be reasoned. Finally, we introduce the question, what other things behave like glue? Thus, the student is required to incorporate scientific information and translate this into further scientific processes. This activity was adapted from a course outline on Bioinspired Materials, developed by one of the authors. For example, a major issue in the field of biomimetics (the study of materials and processes that replicate those found in Nature) is that both students and teachers often get caught up in how we perceive an object and overlook what the object does (Perera & Coppens, 2019). Thus, when we attempt to replicate natural systems in engineering, we focus on what they look like, often resulting in poorly functioning systems as the fundamental processes may be curtailed by the focus on the appearance. Thus, it is important for students to connect to the fundamental processes of materials and their importance so that we can design better materials going forward. Anything the students can think of from the natural world that is sticky or sticks to something is an acceptable response. It might be useful to set a time limit here to allow the discussion to progress further afterwards. From these results pick the top answers, this can depend on the number of groups in the class but the top 3 responses would be useful to consider. Each team can work on one response or, depending on time and class numbers, all teams can examine all responses. Further questions can be introduced, what are the differences between the functionality of glue and the new option? What are the similarities? What would we need to do or know to replace all the glue with this new option? What would be the potential impacts of this choice? Would it be better or worse than the current options? After looking closely at the science of glue and its functionality, the students now have the opportunity to critically evaluate the feasibility, environmental impacts, cost and ethics of their choices, which is similar to the parameters being considered for making the manhole covers round, but more specifically related to their expertise as chemists.

The activities and sequences developed in the previous sections have been modified from activities we participated in as students and found particularly useful in expanding our knowledge of the particular subject area. However, these activities were developed in the context of general education and transferrable skills courses and were not used to promote learning in the chemistry or biology classroom specifically. We have adapted these experiences and activities to what we believe are the needs of learners in chemistry and biology and, which can be used to promote essential skills in natural philosophy for the next generation of chemists and biologists.

The end result of these discussions is that students gain insight into natural philosophical thinking, often referred to as design thinking (Razzouk & Shute, 2012). Importantly, they begin to evaluate options from many perspectives, particularly those outside their own field, before embarking on new processes. Furthermore, they start to make informed choices about the potential consequences of their actions before they even step into the laboratory. We believe that scientists should learn from the very beginning to philosophize their science, that is to question, criticize and analyze what they are taught and how they approach learning, and consider the consequences of their actions. Just because we can do things in the laboratory does not always mean that we should and this evaluation of the process before any work is done is key to integrating this approach in our scientific method. We must give our students the tools they need to be aware of the potential consequences of their decisions, which may have significant impact on the world around them.

It is our opinion that solutions to these challenges will come from those with the ability to confront and criticize the *status quo*. As such, students must have the capacity to critically reflect on innovations and their implications before forging a path ahead (Loeb, 2020; Brouet, 2022; Root-Bernstein & Root-Bernstein, 2022). The suggested outcomes of the activities discussed above are based on our own experiences in learning with similar activities and translating these outcomes to relevant learning outcomes for the chemistry classroom. Critical thinking, reasoning and logic, once so common in the natural sciences, are often missing from the core of natural sciences education (Gare, 2018). This paper is meant to encourage science educators to promote reflection and critical thinking in the classroom, with the aim to revitalize the natural philosophical approach.

Conclusion

So why does science need philosophy? Or more specifically, why does chemistry need philosophy? Chemistry is very much concerned with understanding why systems and processes behave the way they do. Knowing the minute details of a system is often highly regarded and encouraged in our field but such thinking is, in our opinion, useless if there is no conceptualization of how this system exists in relation to other systems, other specialties and other fields. Being exposed to natural philosophical or liberal arts teaching styles as an undergraduate encourages students to think outside the box. Through the learning sequences described in the previous sections we describe simple examples to assist educators in promoting philosophical skills in the chemistry and biology classrooms. Through sequence 1 we describe how students can be encouraged to view objects that exist in their everyday lives with abstract/critical thinking and reasoning. Sequence two introduces students to divergent thinking, logic and further enhances their reasoning skills. Finally, in sequence three we encourage students to build on these skills in a subject specific area and promotes conceptual or design thinking, to push the boundaries of the *status quo* in their area of learning. We believe that a philosophical discussion in the natural sciences is highly beneficial in highlighting how we as scientists fit into the world around us and how we must consider the possible implications that our innovations may have on the ‘equilibrium’ in our own systems.

Philosophical thinking should have a prominent place in the basic sciences; in particular, it should play a critical role in the way we teach chemistry and biology at undergraduate and postgraduate levels. Natural philosophers, like Leonardo da Vinci, Charles Darwin, Ada Lovelace and Émilie du Châtelet, were extraordinary minds of their generations and their innovations have continued to impact the world long after their time. They combined scientific experimentation with deep conceptual thinking, the bedrock of natural philosophy, and it was this combination of approaches that led them to the ideas, for which they are famous. This approach is also crucial to address scientific challenges in a dynamic context, in a world that is changing around us all the time. By giving students the tools to critically evaluate their field from the beginning, they learn to situate themselves and their specialty in the world around them, to confront the *status quo*, gain inspiration across disciplines, assess the viability of new systems and approaches, including monetary and ethical considerations, and propose alternatives to the current system, before taking any specific course of action. These future philosophical scientists, or natural philosophers, are the best tools we have to deal with challenges that currently impact the natural sciences and will continue to do so for many decades to come.

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