The Day the Classroom Flipped: Lessons Learned from Interdisciplinary Science Education Online

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Abstract

The Covid-19 pandemic, evolving needs of students & mentors, and the drive for global educational equality are collectively shifting how courses are packaged/distributed, ushering a more holistic approach and blending of fields. We recently created interdisciplinary courses in chemical biology aimed at massive open online and small private levels. These courses cover biology, chemistry, & physics, and concepts underlying modern chemical-biology tools. We discuss what we learned while creating/overseeing these courses: content optimization and maintaining material freshness while fostering a stimulating learning environment. We outline mechanisms that help sustain student attention throughout rapidly-moving courses, how to integrate adaptability to students' needs in the short & long term, and speculate how we could have improved. We believe this will be an important guide for anyone wanting to develop online learning formats ideal for nurturing interdisciplinary scientists of tomorrow.

Principally due to the Covid-19 pandemic, the last year has enforced numerous changes on the lives and lifestyles of everyone.[1] This impetus has brought significant shifts in how we spend our leisure time, travel,[2] and the ways in which we interact socially and professionally,[3] likely across all disciplines.[4] This strain was heavily felt in academic[5] [6]and industrial scientific circles, that rely heavily on interpersonnel interactions,[7] often through sharing samples,[8] techniques, and in-person seminars.[9] [10] Losses of these vital links and opportunities to share information also impinged, in a gender[11] [12]and disability imbalanced way,[13] on student–mentor/student–student relationships, which have historically been heavily leveraged for training and development of all levels of scientist. Although this may not always have been the case,[14] particularly for work centered on COVID19 research,[15] for us, and we believe likely that of others working in similar areas, especially in developed countries,[16] we have found that interdisciplinary chemical biology collaborations and training have been particularly impacted. This is unsurprising as chemistry, biology and medicinal chemistry are considered some of the areas most affected by COVID19.[17] Furthermore, inderdisciplinary studies are fuelled by free movement of information and personnel between laboratories, departments, and potentially universities/industry[18] and the encouters such opportunities create.[19] Indeed, developing interdisciplinary scientists was already a complex process that is hampered by the traditional structure of universities.[20] Furthermore, many students eschew interdisciplinary science in favor of traditional field-centric routes which offer easier routes to funding[21] and involve less time investment.[22] Thus the pandemic has raised severe concerns for up-and-coming scientists drawn to heavily interdisciplinary areas. Nevertheless, the success of science, and in particular interdisciplinary science, to combat Covid-19 has opened the eyes of wider science communities,[23] [24] and indeed the broader population, to the power of interdisciplinary thinking and research.[1] Thus, it is critical that we harness the interest in science stoked by the pandemic and make the most of the new opportunities posed in the wake of the pandemic by making course content able to nurture and train interdisciplinary scientists of tomorrow.

Several months prior to the start of the pandemic, The NCCR Chemical Biology, a network of 25 laboratories in biology, chemistry and biophysics developing chemical tools to study life at the molecular level, embarked on a project to create a massive open online course (MOOC) and a small private online course (SPOC) focusing on interdisciplinary application of chemistry to the life sciences.[25] These courses are aimed primarily at senior undergraduates but, our goal was to be accessible to starting masters', PhD students, and those looking to retrain. Both courses comprise a series of pre-recorded videos and custom-written texts in which we explain theory and discuss experimental data; supplementary videos where we go into the laboratory, and discuss techniques and instrumentation; and finally computer-graded quiz content. The SPOC contains all the content (i.e. texts, videos etc) of the MOOC, but also has additional professor-guided information sessions and extra problem sets, that culminate in a final graded proposal and oral defence (Fig. 1).The goal of these courses from the outset was to stimulate consilience[26] across physics, chemistry, and biology by taking a unified approach, leveraging the experience within our consortium to provide well-rounded course content, while maintaining a clear structure and progression. Both the MOOC and SPOC have now been available online and at the University of Geneva, respectively, for one year. In this time, the total numbers of learners registered in the MOOC in Chemical Biology is ~10000. Examination of the Coursera website shows that we have achieved above average attendance in the 18-24 age group (reflecting that we have attracted out target group), and a larger than average inscription from those who have a PhD, another goal of our course. As the course was developed and filmed during the Covid-19 pandemic, we were forced to consider how online course content could be best tailored to cope with the new academic teaching and mentoring environment that was thrust on us. During these reflections, we realized that online learning platforms are, to a decent extent, ideal for teaching interdisciplinary science, and can also allow the successful transfer of interdisciplinary knowledge skills similar to what occurred prior to Covid-19. These observations apply especially to the SPOC, but also to the MOOC. It is our goal herein to discuss our personal perspectives that emerged during our development of the SPOC and MOOC and to give pointers on how to get the most out of such courses. We will use our courses as a backdrop, but we believe the points we raise are sufficiently general to apply to many if not all similar courses in the future.

Figure 1. Outline of the two courses (MOOC and SPOC) and their components.

What are interdisciplinary scientists, and how do we assemble a team to nurture them?

Given that the primary goal of interdisciplinary courses is to train and inspire interdisciplinary scientists, we must first ask the question: what is an interdisciplinary scientist? In our view, this is ideally, a researcher equally at home performing and designing experiments involving several disciplines, and also discussing/presenting their results and conclusions to a wider audience. Although such scientists do exist,[27] in reality, such a goal is attainable by a minority.[28] What is more readily achievable, and indeed necessarily common to all interdisciplinary scientists, is the ability to be communicative in numerous disciplines. People with such skills can aid other researchers to understand and evaluate problems from outside of the latters' own field.[29] At the same time, such interdisciplinary scientists can present new solutions to problems from outside of their main area of understanding, using knowledge from their principal area of expertise. Indeed, each field has its own perspective, assumptions and in many instances terms and vernacular, making effectively a "language" and "culture". [30] These differences can prevent inter-field information flow and restrict problem visualization by outsiders.[31] For instance, what is a photocleavable protecting group to a chemist[32], is a photocactivatable molecule to a biologist;[33] once deprotected (photouncaged) the residual protecting group/photocage is an entity requiring separation to a chemist, but can be a cause of artifacts during biological experimentation that require careful design to address.[34] We stress that the conclusion of this discussion is that the science at the chemical level is identical, but the backdrop and goals of the experiments are different. These disparate goals and concerns serve to reinforce the disparate language used across fields and hamper transposition of concepts from one area to another. Indeed, it took almost 20 years for photocaging to transition from the chemical canon to the biological sciences.[32]

Following the above logic, we identified that it is crucial that learners be exposed to field-specific speakers, giving their own perspective in their own words such that learners can experience precise field-specific discussion from a range of perspectives. To reinforce how perspectives differ, and notice how identical core concepts can be applied to ostensibly very different problems in several cases, we identified speakers who leveraged similar experimental techniques (e.g., photocaging or fluorescence) but deployed them differently[35] [30], necessitating varied considerations to a broadly-similar problem or technique. In this way, learners recieve first-hand experience of how different fields/subfields package information and describe it. In traditional *ex cathedra* courses, this approach is not uncommon, but may pose consistency, logistical and scheduling problems. For instance, as organization of interdisciplinary courses is often informal, teaching is not always performed in a setting in which each speaker is comfortable/adequately prepared: many presenters are also not correctly informed of all the course goals, slide organization/standardization, and general themes of the course. Such issues, in our opinion, detract from the overall message of unification that we wanted to present. With an online platform, where content is centrally organized, discussed with all parties involved, and recorded in advance by well-prepared speakers, such issues transpired to be readily addressable.

Identifying topics : Go local for authenticity

Having acknowledged that promoting communication and indeed fluency in several scientific tongues is the bedrock of interdisciplinary courses, we set about considering how to choose course content. We first acknowledged that neither us, nor likely any institution can cover the gamut of interdisciplinary science as it applies to the life sciences. Each university that intends to create a course following our model will likely therefore have to leverage their own specific competences to create their own course. For this reason we have not gone into the specifics of our course too much, but focus on the basic structure, design concepts, and take home messages only. Nevertheless, in most universities there will be sufficient faculty to cover areas spanning biology, chemistry and physics, as it pertains to the life sciences allowing stimulating courses to be developed. In addition to leveraging faculty members from disparate areas, who are particularly well-versed in communication, we resolved to (i) show hitherto unseen data from our own interdisciplinary projects as examples that are discussed in technical detail, and (ii) bring to the fore our own students to discuss the techniques that they use daily in their own laboratories. Point (i) pulls the learners into interdisciplinary science, giving them a taste for discovery by sharing personal unshared data from specific laboratories. Indeed, it is far more exciting to see unpublished primary data from the GFP-labeled beating heart of a transgenic fish collected on our microscopes to illustrate the use of fluorescent proteins, or see data from drug discovery screens illustrating compound induced DNA damage, than mock data or data the students could have found in a text book. This also provides the possibility to display failed experiments, which are rarely present in the literature, but help students to learn to evaluate data.[36] Point (ii) gave us the opportunity to allow our own students to explain how they entered interdisciplinary science, whose laboratory they work for, etc. This was intended to strengthen mentoring and role modeling among our own research students (who at the time were lacking social interaction themselves), and in turn to give some aspirational thoughts to the learners. All the above aspects are considered particularly important for mentoring interdisciplinary scientists.[22] Indeed, we deliberately chose student presenters whose paths were unconventional for the videos to highlight that deviations and changes in career goals are indeed possible and can be effectively achieved. Furthermore, as the student presenters work for lecturers in the course, this gives a further semblance of togetherness, and mentorship that is reinforcing for the learners. Such sentiments were further enforced by filming professors and their students interacting in a seminar session led by an education professional as one of our key discussion videos. Altogether, such content gives an overall high authenticity that is difficult to recapitulate in large courses where instructors and assistants are often recruited based on availability. Such systems are useful for mixed online and in person (blended) courses (like the SPOC), but are particularly effective for all online courses, like a MOOC.

Centralize organization for consistency

As counterpoint, the need to bring in >10 different presenters of different levels of experience, and indeed >5 changes of scenery into the course is prone to lead to a lack of focus, and consistency.[37] We think it is apparent that such shifts in consistency would have typically distracted learners from our key goal of focusing on communication. To sidestep this issue, we implemented a consistent backdrop for all our slides, and ensured all slides were prepared in advance by the same individual, using the same software (Chemdraw for chemical structures, Biorender for biology graphics, and Powerpoint for simple manipulations). To ensure that the speaker's own voice would not be overridden in this process, slides were prepared based on notes from each speaker's courses or their desired content, and all slides were discussed with each presenter at length in preparation sessions prior to final production.

This iterative approach also helped to prepare the speakers for their roles in terms of how to appear on camera and being familiar with course content, while limiting their time invested in harmonizing superficial aspects. This iterative collaborative effort, illustrates the critical nature of having robust ties and understanding between departments, ideally through joint research grants and shared students in place, prior to embarking on a multidisciplinary course.[38] Indeed, as most of the presenters were part of the NCCR Chemical Biology, the insider knowledge that each group has of each other was particularly helpful.

As one of the common weak points of interdisciplinary courses is that they are too varied and have little common thread,[39] we were keen to have clear modules, with obvious and distinct themes so that the learners know where they are going and where they have been.[40] In line with our drive for knowledge unification, these modules were deliberately chosen to blend numerous aspects of scientific fields together,[41] and promote transdisciplinary application of concepts.[42] To do this, we created a simple outline graphic (Fig. 2), which was colored based on the visible spectrum, reinforcing one of the underlying themes of the course (covering fluorescence, protein design, and photouncaging). Each module was given a clear title and the outline built up from first principles, i.e. typically more field-centric concepts, to larger-scale initiatives, either in terms of more detailed biological applications, or higher throughput. Care was taken to refer to previous course material, and reinforce topics already covered when they were reinvestigated in later parts of the course, through the eyes of another presenter. Once again, having course content created centrally significantly aids forming such links as individual lecturers would not be expected to have a global view of the course itself. This overall structure gives a feeling for the learners that they are synergistically building towards something, while also allowing learners to focus on the immediate goals of the course, amongst the variation of speakers and topics. We believe this is critical for interdisciplinary courses, and indeed facilitated by online platforms that require a rigid outline due to filming restrictions.

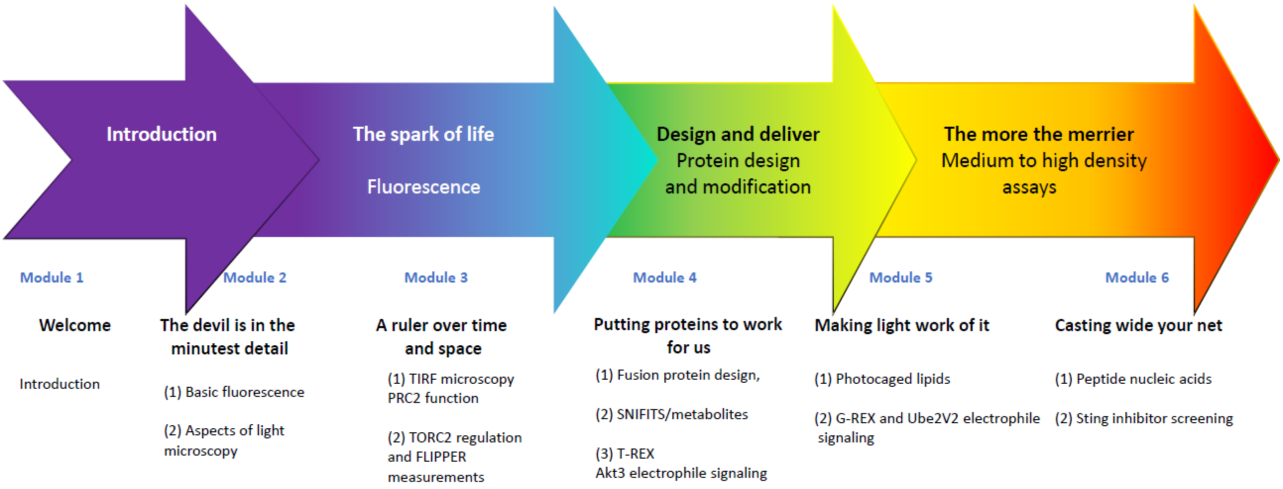

Figure 2. Outline of the two courses, including titles and schematic. Note each module aims to marry concepts from disparate fields to cement understanding, reinforce applications, and help breakdown barriers that exist in tradiaional education frameworks. TIRF – total internal reflection fluorescence; PRC2 polycomb repressive complex 2; FLIPPER a fluoreswcence probe for measuring membrane tension; SNIFITS a technique that uses fusion proteins to sense metabolite concentrations; T-REX a technique that uses photocaged electrophiles to probe cellular signaling pathways; G-REX a technique that uses proteomics to identify electrophile sensors in complex proteomes.

Structuring the course : quantizing video content to maximize output

One of the longstanding catchphrases of education is "less is more".[43] On the face of it, this concept is inherently at odds with multidisciplinary courses. Indeed, multidisciplinary courses strive to show that more is more: i.e. that the sum of the intrinsic parts of physics, biology, and chemistry synergize to create something larger than themselves. Looking back at our previous efforts in interdisciplinary courses, however, we were struck that course content was typically identical to that used by lecturers in their own field-specific courses. Thus: too much information was covered in too little time and the focus was more to rote memorization of facts, rather than being able to describe or explain how interdisciplinary concepts were deployed. Oftentimes, information presented was redundant, for instance, discussing a range of protecting groups, cell lines, or experiments that lead to the same outcomes. Initially, our goal was not to change this stratagem. However, filming limitations, and restrictions on class time, etc., forced us to rethink. What came out of our discussions was that video content is best quantized into 5–10-minute segments, and that by picking our examples carefully we could cover multiple overlapping and mutually reinforcing concepts simultaneously and concisely.[44] Indeed, our analysis is consistent with that of others who have concluded that video teaching tends to lead to the removal of seductive details.[45] Indeed, the quantization imposed due to the nature of online courses made us appreciate that each video must be itself a journey. In this way, extending the story arch is more important than covering a panoply of similar examples of a single procedure. For instance, when faced with multiple possible topics for high-throughput screening of encoded chemical libraries, we deliberately chose a story going from an initial screen to a target molecule, to chemical biology-based affinity procedures, via discussion of protease function and recognition.[46] This way, learners saw the utility of molecules from screens, and were introduced, serendipitously, to proteases, a crucial class of enzymes and important drug targets (including for Covid-19).[1] The story arch going from a tube to more complex biological experiments with mechanistic insights further serves to highlight how interdisciplinarity naturally leads to application. Other examples of this strategy include modules covering TORC pathway regulation (encompassing the interface of physical forces, molecular sensors, and pathway signaling)[47] and STING pathway inhibitors (encompassing structure activity relationships, mechanistic analysis, and drug screening)[48] that we also discussed in the course as other examples of druggable pathways/proteins, distinct from proteases. In our model each university would choose examples most pertinent to their own research that depict journeys covering diverse scientific concepts, highlighting the story arch.

Overcoming inherent obstacles

One significant issue with online pre-recorded video content, especially in multidisciplinary areas is the rapid changes that are made in interfacial fields.[49] Thus, there is a possibility that online content as well as the visual format used to convey the information, can rapidly become dated. Our model is admittedly rigid, and hence provides no complete solution to this problem. Shooting videos to supplement existing content, or, especially, writing new texts are workable patches which are compatible with the Coursera platform. Other more flexible models of online education, such as explaineverything,[50] could certainly present more ready workable solutions as they allow more informal educational videos to be created that can be shot at low budget, rapidly, potentially in a decentralized way. However, such approaches would in all liklihood suffer from lack of homogeneity, formality, and rigidity which are a key part of our model. In our case, aside from being prepared to provide supplements as needed, we chose to focus the content more on fundamental aspects of each topic, rather than gravitating to the latest papers/findings. Our thinking was that although fundamental concepts can shift, these concepts are much less subject to rapid change than vogue papers, or techniques. Fundamental ideas are also often more generally applicable than the latest findings.

Interdisciplinary science is traditionally associated with complexity and indeed enabling innovative solutions to complex problems,[51] and overall project success[52] which is good for both society and the individual's sense of satisfaction.[53] Indeed, there exists strong and reinforcing links between creativity and interdisciplinarity.[54] [55] But how can you promote creativity with primarily online content? In the

SPOC, we dealt with this through implementing a written proposal and oral defence, and in-person or Zoom-based meetings with professors to discuss course or proposal content. We further created a written pamphlet that discusses how to write a research proposal, and shows the grading scheme. Learners also have time to discuss with the professors who will grade their written work, about problems they are having with their proposal and their overall outline. The MOOC on the other hand, has no such mentoring opportunities and all quizzes are graded automatically, meaning we needed new ways to stimulate creativity. One function we found very useful, especially for topics on protein design, and chemical compound design, was quizzes using drag and drop (for instance those offered by H5P). These give learners the opportunity to get creative, and through automated quiz feedback they can see if their efforts have been successful. This sort of content has already been linked to successful online course development.[56] Of course, there is significant scope for improvement, such as though new software design, open-access seminars related to the course, or new readings, either of primary research papers linked to topics, or topical reviews tailored to the course (which could be published separately or added to the course). Virtual reality opportunities would also improve the experience even more, and further improve accessibility. We will be working with education professionals to improve this aspect the most in the future online courses we create.

Nonetheless, it is important to understand that by breaking down the field structure that has been traditionally erected to help students conceptualize science, we can equally stimulate problem solving.[57] We further propose that in a field-fluid education system, innovative solutions to problems posed will be more likely. In this aspect, the MOOC remains somewhat restrictive, but the SPOC is a perfect forum.[56]

Education is a life-long commitment

Our consortium has been particularly involved in applying interdisciplinary concepts to important scientific problems. Several within the NCCR Chemical Biology have been involved in Covid-19 research[58] or have discussed the response of science to Covid-19 generally[1]. Our outreach programs are further gearing up to meet shifting needs of students from high-school and above in Switzerland and beyond. By bringing a course online, especially in the setting of a MOOC, or something similar, learners are naturally encouraged to be inquisitive about the lecturers and their commitment to education and interdisciplinary research. It is thus crucial that departments aiming to embark on such a course strengthen their outreach, education, and interdisciplinary ties such that their all-round effort to be attractive to their target audiences in what is likely to be an increasingly competitive area of education.

Outlook

In summary, we think that there are several benefits to online teaching over in-person, *ex cathedra* variants that makes the online format ideally suited to training interdisciplinary scientists. Firstly, online content allows opening of the classroom to audiovisual materials not easily integrated into a traditional course. This is readily shown by the “in the laboratory” videos discussed above, but could easily be extended to purely technical videos, seminars, or prerecorded question and answer sessions, a pilot version of which was included in our course. Secondly, online content is necessarily quantized differently to traditional *ex cathedra* teaching. 10-minute-long videos shot professionally, offer an enriching environment that necessitates rethinking of course material, trimming away a lot of unnecessary information. With care and attention, the environment can thus be tailored to increase focus on learning overarching concepts, as well as stimulating critical thinking and creativity. Finally, there is a large amount of control that can be exerted through online teaching that is less accessible to traditional interdisciplinary courses, imposed through, for instance, the need to carefully plan filming. The keypoints suggested throughout the text are summarized in Fig.3.

In conclusion, although we find ourselves in a very different post-Covid-19 world, we believe that there are new educational opportunities stemming from this situation that are ripe for aiding learners and mentors alike. Our consortium will continue to strive to improve online education and hope to partner with like-minded groups in the future.

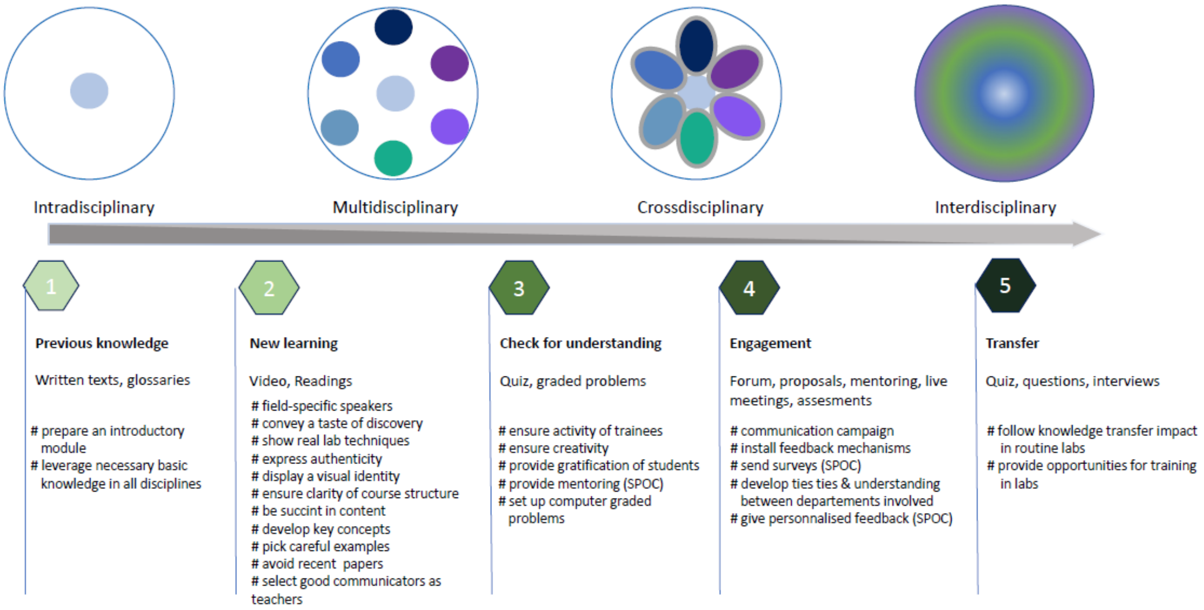

Figure 3. (Upper) The multiples ways of viewing science, from field specific, to multiple separate fields, through to interdisciplinary (consilience). The outer blue circle depicts the gamut of knowledge applicable to science. (Lower) methods deployed in MOOC and SPOC to ensure effective knowledge transfer and learning.

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All authors were involved in all aspects of manuscript preparation.

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