ARTICLE

Redesigning a PhD Course to Promote Interdisciplinarity and Cultivate Key 21st-Century Skills: An Exploratory Study

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ABSTRACT

There is a growing yet unmet need for PhD curricula to cultivate skills needed to confront 21st-century challenges. One such skill is interdisciplinarity, which is deemed essential for dealing with various complex problems such as climate change, antibiotic resistance, and sustainability. When we reflected on the nature of our "Integrative Sciences and Engineering" course, we found that the emphasis was on content knowledge and didactic modes of instruction rather than on teaching students the definition and process of interdisciplinarity. Hence, we redesigned part of the course to promote interdisciplinary learning more explicitly. To do this, we consulted the literature on interdisciplinary graduate education, which suggests that interdisciplinarity be operationalised as collaboration in a STEM context. Thus, we adopted from the literature a model designed to promote interdisciplinary thinking. We also introduced blended learning to provide our students with a means to practice interdisciplinarity and thus collaborate more effectively. To assess the effectiveness of these interventions, we sought to answer two research questions: (1) What was the impact of the model and blended learning on promoting interdisciplinary thinking and collaboration? (2) How did the students perceive these changes? To answer these questions, we analysed students' discussion forum posts, instructor and peer feedback, group presentations, and results of surveys and interviews. Our findings suggest that the model and blended learning approach function synergistically to help students think and act in an interdisciplinary way, and that students were generally receptive to these changes. We expect that our work will be relevant to the scholarship of interdisciplinary graduate education as well as to current efforts aimed at reforming doctoral curricula.

Keywords: PhD curriculum, blended learning, discussion forum, instructor feedback, peer feedback, science education

INTRODUCTION

To face the challenges of the 21st century, some have called for an overhaul of doctoral programmes so that PhD students are trained to be thinkers rather than just specialists. The ability to think innovatively and across disciplinary boundaries has been identified as one such skill by those calling for such reforms (Bosch & Casadevall, 2017). Interdisciplinarity is becoming more and more important because problems in the real world "rarely arise within orderly disciplinary categories, and neither do their solutions" (Palmer, 2001).

The Graduate School for Integrative Sciences and Engineering (NGS) at the National University of Singapore (NUS) runs a full-time research-intensive PhD programme that lasts four years. In the first two years of their PhD programme, our students have to complete a core curriculum consisting of three courses. One of these courses ("Interface Sciences and Engineering") was established to encourage interdisciplinarity amongst our students. However, the course is characterised by didactic instruction and summative assessments that prioritise students' content knowledge. Instead of equipping students with interdisciplinary skills needed to deal with the complexity of 21st-century challenges, the current approach merely exposes them to a selection of research topics in a traditional classroom setting. We thus sought to revise the module to cultivate such interdisciplinary skills, which will stand our students in good stead during their PhD research and beyond.

LITERATURE REVIEW

As part of our effort to undertake curricular reform, we consulted the available literature on interdisciplinary graduate education. We found only a few examples of attempts at curricular reform at the doctoral level. For example, Lorsch and Nichols (2011) describe how Bronson et al. (2011) shifted from a disciplinary to an interdisciplinary focus by reorganising their curriculum into three ''nodes'' (N) and introducing two parallel integrative courses that draw ''connections'' (C) between these nodes. This updated curriculum was designed to facilitate content delivery across scales in an integrative manner and thus help to forge interdisciplinary research collaborations. The importance of interdisciplinary approaches in contemporary biological research is increasingly recognised in a culture where most graduate students are still receiving the traditional form of research training that focuses on individual disciplines (Bronson et al., 2011).

Wagner et al. (2012) describe a "Distributed Graduate Seminars" (DGS) model in their landscape genetics course. The DGS deploys web-based technology to equip both students and faculty members with skills for engaging in research collaborations, and to provide them with a common language and knowledge base. In recognition of the fact that no single research group has expertise in both population genetics and landscape ecology, this model was designed to overcome barriers to scientific communication and collaboration across these disciplines. Thus, the authors developed a new graduate course that trains students to collaborate across institutions in an online environment.

Similarly, in the realm of sustainability science, collaborative skills are essential for addressing the world's most pressing and complex sustainability problems which, due to their social, natural, and engineering science dimensions, are inherently interdisciplinary in nature (Knowlton et al., 2014). In their course, students participated in face-to-face (F2F) sessions to discuss readings, online discussions, and graded assignments[1]. One key recommendation that emerged from this pilot study was to place a stronger emphasis on helping students from different disciplines develop a common scientific language through collaboration.

In search of relevant learning objectives for our own STEM-based programme, we reviewed the pedagogical literature on the U.S. National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) programme. To propose learning outcomes for science and engineering graduate education, Borrego and Newswander (2010) combined practical knowledge from science and engineering faculty with humanities-based interdisciplinary education literature. When they analysed 129 successful proposals submitted to the IGERT programme, they found that many interdisciplinary courses emphasised collaboration. They concluded that science and engineering faculty tend to operationalise interdisciplinarity as collaboration, a finding corroborated by literature from humanities scholars such as Repko (2008, p. 44), who described interdisciplinarity amongst scientists and engineers as frequently being a collaborative process:

> An expert interdisciplinarian is one who is able to integrate the input of others to address an issue, which may include coordinating team members. This trait applies especially to interdisciplinarians engaged in technical and scientific studies that most commonly involve teamwork.

In addition, Borrego and Cutler (2010) wanted to ascertain the extent to which desired learning outcomes, activities, and assessments were constructively aligned. An analysis of 130 funded proposals from the IGERT programme revealed that constructive alignment was generally lacking. Their recommendations were to define clear learning objectives, seek assessment expertise, and constructively align different elements of the curriculum.

Several common themes emerge from this literature. Firstly, collaboration is essential for promoting interdisciplinarity in a science and engineering context. Secondly, online platforms are useful in fostering collaboration. Thirdly, faculty members felt there was a need to redesign their courses to make them truly interdisciplinary. It should be noted, however, that these examples are all from the North American context and therefore may not be wholly transferable to our Asian context. Nonetheless, we took the above approaches into consideration when deciding how to redesign our module. Hence, in sharing our experiences and providing insights on the kinds of reform that were well received by students, especially in the Asian context, our current study would thus contribute to the field of interdisciplinary graduate education.

REDESIGNING THE INTERFACE SCIENCES AND ENGINEERING MODULE

In line with the general need for doctoral reform, we decided to redesign our own Interface Sciences and Engineering (ISE) module. ISE is a compulsory module that students are required to take before their PhD qualifying examination. It is taught over 10 weeks and covers five topics, with two weeks being allocated to each topic. Each topic is taught by different lecturers. Thus, only the first topic, conducted by the corresponding author (who was also the course coordinator), was redesigned. It was hoped that if such changes were effective, other lecturers could be persuaded to change their mode of instruction in similar ways for future iterations of the course.

A typical class of 24-30 individuals would include students from biology, chemistry, computing, engineering, mathematics, and physics. Thus, conditions are ripe in this course for promoting collaboration between students representing multiple STEM disciplines where previously, the course focused on delivering content knowledge about certain topics in science and engineering.

INTRODUCING A NEW TOPIC: MICROBIOMES AND SUSTAINABILITY

To encourage students to think about the complex problems facing society, we introduced "Microbiomes and Sustainability" as a new topic into ISE. At a recent conference on the above theme, one of the keynote speakers, Alexander Zehnder, claimed that Earth's microbiomes (also known as microbial communities) are fundamental pillars of sustainability (Zehnder, 2017). He argued that microbiomes have strong connections with eight of the United Nations' 17 Sustainable Development Goals (SDGs). Zehnder concluded his talk by advocating that educators place more emphasis on the role microbiomes would play in securing a sustainable future. Thus, for the new topic, we wanted students to think about how microbiomes could contribute to sustainability and do so in an interdisciplinary manner.

Given the topic's complexity, the definition of interdisciplinarity that we adopted was that of Repko and Szostak (2017). They define interdisciplinarity as a "process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding" (Repko & Szostak, 2017, p. 21). Complementing this definition is their "Integrated Model of the Interdisciplinary Research Process (IRP)" ("Broad Model" for short), which is designed to promote interdisciplinary collaboration. The model is divided into two main parts—"drawing on disciplinary insights" and "integrating disciplinary insights" (see Appendix 1 for full version of the Model). The Broad Model emphasises integration of disciplinary insights as the hallmark of interdisciplinarity (Repko & Szostak, 2017). Thus, in our opinion the Broad Model would promote interdisciplinary thinking and collaboration amongst our students by making both the definition and process of interdisciplinarity explicit (Rashid, 2019). By enabling individuals to apply their training to new contexts such as the "Microbiomes and Sustainability" topic, the interdisciplinary process is expected to embolden individuals to handle complex problems without feeling pressured to cling to their own disciplinary perspectives (Repko et al., 2017).

INTRODUCING BLENDED LEARNING

The corresponding author consulted colleagues at our university's Centre for Development of Teaching and Learning (CDTL) for advice on how to make the module less didactic. Furthermore, based on experience it was evident that students were usually quite reserved during F2F classes. As discussed elsewhere, this latter problem seems to be commonly encountered in the Singapore context (Rashid, 2019). Thus, there was a need to create opportunities for collaborative discussions in a "safe" environment outside the classroom. On the advice of our colleagues at CDTL, we introduced blended learning into the course for the first time. Blended learning is defined as the "organic integration of thoughtfully selected and complementary face-to-face and online approaches and technologies" (Garrison & Vaughan, 2008), which we believed would enrich students' learning experiences beyond what is possible within the traditional classroom (De George-Walker & Keeffe, 2010). We also hoped that by introducing technology, students would continue interacting and collaborating with each other outside the classroom and thus put the Broad Model into practice.

To redesign the module, we introduced the following activities for the topic "Microbiomes and Sustainability" (Figure 1). Our students first participated in an F2F lecture which introduced the instructor, the module outline and instructions for the first topic. Next, they were split into groups comprising students from various STEM disciplines to commence group discussions on the assignment under the instructor's supervision. Afterwards, they had to watch a series of video lectures that introduced the topic "Microbiomes and Sustainability". For one week, they participated in online activities which included an asynchronous discussion forum to promote dialogue between students, and a feedback exercise in which they commented on their peers' presentation outlines. Rubrics were provided to the students at the start of the course.

The instructor provided feedback on students' presentation outlines in the middle of the week. Each group was assigned a "partner group", and respective partner groups exchanged questions as peer feedback by the end of the week. After completing the online activities, students delivered F2F group presentations, with additional time allotted for questions and consolidated F2F feedback from the instructor.

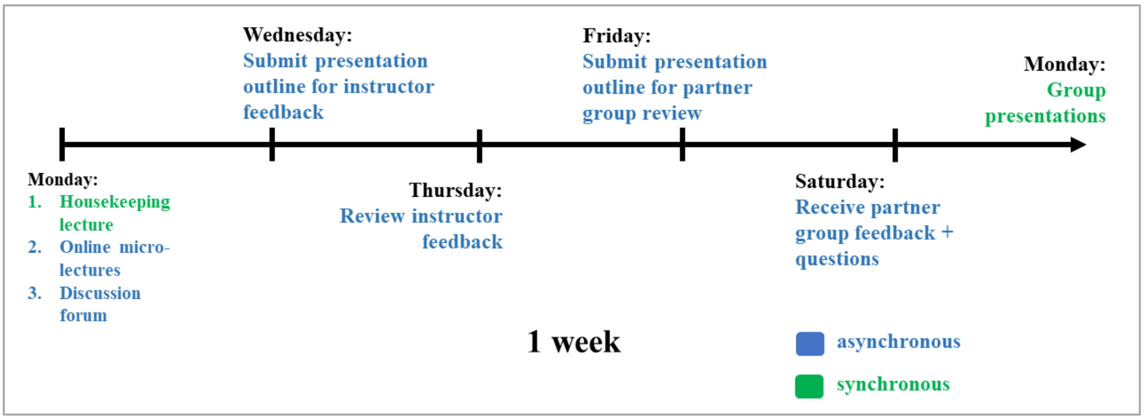

Figure 1. The format and duration of the topic "Microbiomes and Sustainability".
The blended learning format featured both asynchronous (blue) and synchronous (green) activities.

PURPOSE AND GOALS OF THE STUDY

The purpose of this pilot study was to explore whether the Broad Model, combined with blended learning, would be useful in promoting interdisciplinary thinking amongst our students. The goal of this study was to test the effectiveness of the above framework and format in promoting collaboration amongst students representing diverse STEM disciplines in an Asian graduate classroom.

RESEARCH QUESTIONS

This study addresses the following research questions:

1. What is the impact of the Broad Model and blended learning on promoting interdisciplinary thinking and collaboration?
2. What are students' perceptions of the effectiveness of this approach?

Addressing these questions is important for achieving some of the goals of doctoral programme reform outlined in the Introduction.

METHODOLOGY

Participants

With approval from our Institutional Review Board (IRB-S17-367), twenty-nine PhD students (20 males and 9 females) participated in this study. All of them were enrolled in the ISE module. The redesigned topic consisted of both online and F2F sessions. The online component was delivered via the "Integrated Virtual Learning Environment" (IVLE), the university's learning management system (LMS) at the time of the study.

Analysis of students' work

We looked at students' forum posts and final presentations for evidence of the extent to which they were able to apply our new framework in their discussions and how it influenced their final presentations. It must be emphasised that, since this was the first time we were introducing these changes, it was not our intention to find out how effective these interventions were, as compared to having no intervention, as there was no fair basis of comparison (students worked on something completely different during previous semesters). Instead, we hoped to see qualitatively how students applied this framework and whether it was useful for them.

Surveys and interviews

To better understand students' perceptions of our interventions, we conducted surveys and interviews. Guided by the literature on interdisciplinary learning theory and blended learning, we designed both the survey and interview guide ourselves. The survey and interview guide included questions about the effectiveness of the blended learning environment, instructor feedback, peer feedback, and the interdisciplinary framework in promoting interdisciplinarity. The survey contained a mix of quantitative and qualitative questions, and the interview guide comprised open-ended questions (see Appendix 2 for the full survey questionnaire). For the survey data, we tabulated the results and calculated the percentage of responses for each choice. Notes taken during the interview were analysed for common themes and were compared with the survey data to reveal any correlations.

FINDINGS AND DISCUSSION

In this section, we present our analysis of discussion forum posts, instructor and peer feedback, and student presentation content to reveal the impact of the framework and blended learning (the latter referring to discussion forums, instructor and peer feedback, and the two F2F lectures) on interdisciplinary thinking and collaboration. We analysed the collated survey and interview data to reveal our students' perceptions of these interventions. Lastly, we suggest improvements.

Online forum discussions

Based on the literature that we surveyed and requirements of the new topic, we set two learning objectives for our students: (1) to argue for the role that microbiomes could play in environmental sustainability by drawing on insights from different disciplines, and (2) to engage in collaboration by integrating ideas from classmates representing multiple disciplines. The class was divided into groups of five students who would collaborate to prepare presentations on the link between microbiomes and one of the United Nation's SDGs.

To promote sharing of disciplinary insights, students were instructed to rely on the Broad Model, with a focus on stating the research question, identifying relevant disciplines, and integrating their ideas. As part of blended learning, we introduced asynchronous online discussion forums to promote collaboration between group members outside of the classroom.

Figure 2 and Figure 3 show representative forum posts from two groups. Their posts show that they have considered and utilised the Broad Model to guide their thinking, which later helped them produce better interdisciplinary solutions in their presentations. For all posts, student's names have been redacted to protect their privacy.

Reply : Re: Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 16-Jan-2018 04:18 PM
Hi [redacted]

Grp 1 Member B

I do agree with you that we should first define all the terms that we are using (i.e. good health and well-being) so everyone is clear about what we are talking, what is/are the problem/s and possible solutions.
Nevertheless, this microbiomes-humans relationship is a reversible one (they affect us, but we also affect them; and, in a way, there is a vicious circle involved). Hence I think we can also discuss this matter.
As scientists, we definitely need evidence for whatever we are stating/claiming in our presentation. Personally, I would identify some problems regarding humans' well-being that are of immediate concern and then find solutions for those, solutions that involve harnessing the microbiomes (within and outside our beings).
Moreover, let's not forget about the social and economic implications. I think I can give more input on this once we have a clearer idea about the points we are going to address in the presentation.

Also, I am intrigued by your proposal of coming up with new, out of the box ideas. But let's not forget that the presentation is 20 minutes max, and I have the feeling we will have a lot to talk about, so we need to be efficient. For this I would propose to find a solution to which we can all contribute, instead of proposing a new idea for each field we are working in (for short, let's go for interdisciplinarity, not for multidisciplinarity).

I am also looking forward to the others' opinions. And maybe we can get more specific? I feel that we are looking mostly at the big picture.

Topic : Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 16-Jan-2018 10:01 AM
Hi all,

Grp 1 Member A

A quick read through the paper and I feel that the environmental microbiome controls a broad range of facets of our well being. These facets run the gamut from genetic wellbeing to cognitive wellbeing with arguably, everything else that we can possibly think of falling somewhere in between.

So, I suggest that we follow the SDG approach (first the goals are listed down and then individual goals are checked against whether or not these environmental microbes play a role in acheiving that goal. Conclusion: Microbes are responsible for 11 of 17 goals) — we brainstorm amongst ourselves and list down what we mean by good health and well being (are there defined standards to classify what falls under the rubric of good health? — actionable item: brief survey). Once we list down the various possibilities, we then try to re-read the paper and do a bit of survey to find conclusive evidence if the environmental microbes play a role (can be harnessed) to achieve each one of them. This approach, I reckon, is structured and can serve as a basis for outlining the presentation.

Also, since the whole point of this presentation is to foster interdisciplinary research (and not so much about the content), we can use this opportunity to think outside the box. As for me, reflecting on what I can bring to the table as a computer scientist, the first thing that comes to my mind revolves around communication among microbes to form biofilms (a bit of background — last sem I had delivered a presentation on biofilms in Dr. Rafi's journal club and was quite intrigued by the communication among microbes for the formation of biofilms). As part of the presentation, we can discuss an approach of harnessing (and manipulating) this communication to achieve well being. I suggest an understanding of the various methods (parameters) of the communication. If we have this understanding, we might try to find ways of tapping into and disrupting the quorum sensing (this is how the microbes communicate) and also try to manipulate individual parameters of that communication to tweak it to our advantage. (Outline. Does biofilms sabotage good health and well being? Is there a defined subset of identifiable microbes responsible for the formation of biofilms? What is the communication pattern that these microbes adopt to facilitate the formation of biofilms (or, what is the underlying mechanism of quorum sensing? Can we map the communication into bits (digitization)? If we alter the bits of the communication with the intention of disrupting and/or altering the message, can we predict how alteration of individual bits affect the communication? Can we predict the altered message? If we manage to develop an understanding (in part or in whole) from the previous questions, we may try looking at the bigger picture — Do microbes communicate for other purposes? What are the purposes? Do they follow a mechanism similar to quorum sensing? Can we hack into this communication and skew the communication to our advantage (well being)?

Similarly, we can all talk about something outside the box from the perspective of our individual research areas. This might sound far-fetced, but you never know, might be we are digging up a gold mine and a revolutionary idea is lurking beneath waiting patiently to be dug up by the members of our group!

I would be looking forward to your feedback on what you think of my idea for the outline.

Grp 1 Member C

Reply : Re: Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 16-Jan-2018 08:12 PM
Hey both,

Many thanks for your sharings and suggestions for the presentation outline. I do agree that setting clear and concise definitions for the terms involved in our research question would be a good way to pave for the presentation flow to come. Perhaps a focus on extended lifespan, reduced morbidity and enhanced bodily functions may be good to address and define good health and well being. Since the target audience involves the coursemates who would be equally familiar with the UN's 17 SDGs, may be we can skip that and move in direct to our targeted SDG: Good Health and Well Being.

Though trying bring in new, out of the box ideas for the short 20 mins presentation may be quite ambitious, I think trying to include the interdisciplinary approach may be a valuable consideration, especially since we would be brainstorming towards real, practical solutions to the problem. I reckon we can try a short preliminary sharing (just 2 - 3 slides) on how we think our various disciplines can each provide solutions, or parts of a solution for an overall collaborative picture towards harnessing microbes for the targeted SDG (e.g. computational simulation specific to certain microbe function + chemical/physic characterization of activity + biological understanding of intended outcome/effect)

Other than that, I gathered from the paper that microbiomes for good health and well being may revolve around some of these point:
- Symbotic functions: Functions in Chlorophyll and Mitachondria
- Immune development: Immune perturbation, activation and Antibiotics development
- Chemical Synthesis: Synthetic pathways and contributions to development of drugs, antibodies, pharmaceuticals
- Microbial functions: Enhancing body functions - Prebiotics and Probiotics

Just some ideas. Would be good to get your feedbacks. Thanks :)

Grp 1 Member D

Reply : Re: Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 17-Jan-2018 10:02 AM
This is succinct. The aspects that you've outlined is easier to digest in a presentation, embodying the interdisciplinary facet altogether. I think it will be much more focused if we could simply define the terms health and well being, and work towards uncovering major findings establishing the potential of microbes or even recent discoveries that has highlighted their importance in health, followed by a discussion of pros and cons.
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Grp 1 Member E

Reply : Re: Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 17-Jan-2018 10:10 AM
Yes,

Since we have all come to a consensus on the scope of work I think the next step is to brainstorm on the scope in detail and maybe split the work for each to take a different topic, while bearing in mind that we need to merge them all together to fit one nice presentation with a good flow and strong mesage!

Grp 1 Member A

Reply : Re: Ideation (Rapid Brainstorming) for scaffolding the outline
From : [redacted]
Date : 18-Jan-2018 03:28 PM
Thanks, [redacted] for sharing the four papers explaining how microbes play a key role in reducing our carbon footprint and thanks, [redacted] for sharing the read on why well-being matters. Both of these should indeed come in very handy for our presentation.

As I had mentioned in my first post and as has been highlighted by Dr. Rafi both in his feedback and in his email, this presentation opens up a niche opportunity for some interdisciplinary thinking. So let us, over the next few days, discuss on how we can contribute towards achieving this goal. There are two possible approaches —

1. Each of us pick a sub-issue of well-being and talk through the solution from the perspective of our own research area (like [redacted] talking about how microbes help reduce our carbon footprint, I may talk about quorum sensing and microbial communication patterns etc.); OR
2. We try to think of a central issue that is directly related to our well-being (and I think this should be narrowed down from the generic umbrella term - "well-being"). Once we decide on the issue, we can each contribute by lending our own perspective towards solving this issue.

Either approach works for me, though I guess, I would be leaning a bit more towards the second as it blends in perfectly with the very idea of interdisciplinary collaboration ([redacted] had talked about this in one of her earlier posts). Also, I believe, this would force us to think outside the box and make for an interesting part of our presentation. Later, we can evaluate our collective position as a group on tackling the issue and talk about how we believe we can collaboratively work towards a feasible solution.

I suggest we reach a consensus on the approach to follow and brainstorm on the central issue we can address by pitching our interdisciplinary ideas.

Figure 2. Students discussing how their own disciplines would be relevant to solving the interdisciplinary problem.

Group 1 appreciates that the problem is complex in nature and rightly argues for an interdisciplinary approach in which they would all contribute to the solution through integration, the hallmark of interdisciplinarity (Figure 2). They understand that an interdisciplinary approach is necessary for them to come up with realistic solutions, which is consistent with the definition of interdisciplinarity as a process of solving a problem that is too complex to be dealt with adequately by a single discipline. They put the Broad Model into practice by suggesting how their respective disciplines are relevant to the problem, e.g. how computer science might improve our understanding of how communication occurs between microorganisms within biofilms. Having agreed on the scope of their project, they proceed to split the work between them, start contributing their ideas, and prepare for subsequent integration, indicating that collaboration is happening. In addition, they agree to evaluate their solution as a group. They indicate that the problem's complexity requires them to think outside the box as they articulate and integrate knowledge from their respective disciplines. As the discussion ensues, they begin to appreciate how their ideas converge to address the complexity of their assigned SDG of "Good Health & Well-Being", and decide to explicitly show in their presentation how they think their respective disciplines are relevant to their solution, thus demonstrating how they have collaboratively worked towards said solution.

Reply : Re: Zero Hunger - Food security, nutrition, agriculture
From : [redacted]
Date : 20-Jan-2018 10:59 PM
How can we harness Earth's microbiomes to achieve "zero hunger"?

Grp 2 Member A

Zero Hunger

· Sufficient food supply

· Sufficient nutrients

How?

· Synthetic biology:

o Genetically engineering microbes; Man-made micro-organisms

Synthetic biology – Food producing microbes

· Capable of producing nutritional compounds/supplements

o Comparing to synthetic methods – safer, less waste/toxic by-product

o Lower cost of production? Higher yield?

· Personalise diet

o Every individuals will have specific diets/nutritional demands specially cater for them

o Optimising nutrient consumption

· Food producing microbes

o Synthetic proteins; lab-grown foods

Synthetic biology – Agricultural microbes

· Microbes that secrete chemicals to increase growth/yield

o Eg. plant hormones

o Probiotics for plants

· Microbes that protect plants from pests/diseases

o Cross-talking with existing plant microbiome to improve their health

o Bio-pesticides? To help kill pests? Kill weeds?

§ Able to use less chemical pesticides/herbicides

Synthetic biology – Livestock farming microbes

§ Probiotics for animals

o Improve health; less disease prone; disease free

Topic : Roles of microbiome in food sustainability
From : [redacted]
Date : 16-Jan-2018 01:24 AM
I picked up several ways in which microbiomes may have a role in working towards "Zero Hunger":

Grp 2 Member B

1) Improving land fertility by nitrogen fixation thereby improving agricultural yield:

Generally, there are about 50 billion microbes in one spoonful of soil. The microorganisms' primary role is to break down organic matter to obtain energy. Microorganisms help release essential nutrients and carbon dioxide and perform key roles in nitrogen fixation, the nitrogen and phosphorus cycles, denitrification, immobilization, and mineralization. Microbes must have a constant supply of organic matter, or their numbers will decline. Conditions that favor soil life also promote plant growth.

- Immobilization (assimilation) – uptake of inorganic-N from soil and incorporation into organic-N compounds in microbes (N becomes unavailable to plants)
- N-Fixation – conversion of N-gas in the air to organic-N that becomes available to plants (performed by bacteria associated with roots of legumes and other plants, and some free-living soil microbes

2) Improving crops' uptake of crucial nutrients from soil hence its eventual quality and nutritional value:

Three mechanisms are usually put forward to explain how microbial activity can boost plant growth: (1) manipulating the hormonal signaling of plants; (2) repelling or outcompeting pathogenic microbial strains; and (3) increasing the bioavailability of soil-borne nutrients.

In natural ecosystems, most nutrients such as N, P, and S are bound in organic molecules and are therefore minimally bioavailable for plants. To access these nutrients, plants are dependent on the growth of soil microbes such as bacteria and fungi, which possess the metabolic machinery to depolymerize and mineralize organic forms of N, P, and S. The contents of these microbial cells are subsequently released, either through turnover and cell lysis, or via protozoic predation. This liberates inorganic N, P, and S forms into the soil, including ionic species such as ammonium, nitrate, phosphate, and sulfate that are the preferred nutrient forms for plants.

Also, providing agriculture systems with macronutrients through the application of mineral fertilizers is an unsustainable fertilization practices due to rapidly diminishing phosphate rocks and the greatly energy-intensive Haber– Bosch process. One possibility is to replace mineral fertilizers by organic inputs, and to supplement plants with specific root-associated microbes that are able to break the organic matters down. Since organic inputs are comparatively much more sustainable than mineral fertilizers (due to myriad agricultural, industrial and municipal processes producing huge volumes of nutrient-rich "waste"). Another factor is that organically bound nutrients are more stable in the soil compared to mineral fertilizers, and therefore less prone to leaching and volatilization.

3) Microorganisms may aid in reducing susceptibility of crops to diseases and pathogens thereby increasing overall yield:

A number of soil factors and management practices affect root growth, distribution, and health. Cultural practices that promote soil biodiversity help maintain healthy root systems, because an active and diverse microbial population competes with root pathogens and can reduce root disease. Research into soil microbiota has shown how some species can enhance plant defences against infection. However, other species can cause problems. For instance, Rothamsted Research found one strain of bacteria that removed nitrogen from the soil. This depleted the nutrients needed for plant growth and created greenhouse gases.

Examples:
Trichoderma spp.: These species are attributed to a variety of physiological, antifungal and insecticidal effects. It acts against a broad spectrum of plant pathogens. These fungi increase plant growth and development, but also development of root system. It has also been observed that selected *Trichoderma* strains can improve plant nutrients' uptake. Increased growth occurs due to its strong anti-pathogenic activity, biosynthesis of hormones, improving nutrient uptake from the soil, root development by increasing metabolism rate of carbohydrates and increased photosynthesis.

B. amyloliquefaciens is gram-positive,aerobic, and endospore-forming bacteria, beneficial agents for plant growth promotion and suppression of soil-borne diseases in agriculture. *B. amyloliquefaciens*produces many metabolites such as e.g. enzymes, and many types of antibiotics, which inhibit growth of fungal pathogens.

4) Improve individual's microbiota hence their ability to absorb nutrients more efficiently from the food consumed:

Billions of friendly bacteria are living in our digestive tract, the most commonly commercialised ones include *Lactobacillus* and *Bifidobacterium*. In our gut, good bacteria can displace bad bacteria and influence our overall health, metabolism, digestion, and body composition. Gut bacteria also help to synthesize Vitamins B and K and enhance digestion and nutrient absorption while controlling the growth of other pathogens

The stomach and proximal small intestine are responsible for most nutrient digestion and absorption in humans. In an healthy individual, the indigestible carbohydrates and proteins that the colon receives represent from 10%–30% of the total ingested energy. Without the activity of the colonic microbiota, these nutrients would generally been eliminated as stool without further absorption because the human large intestine has limited digestive capability. Hence, modifying the gut microbiota may be one of the possible strategies to counter undernutrition.

Reply : Re: PLACEMAT DIAGRAM
From : [redacted]
Date : 21-Jan-2018 10:12 AM
[redacted]

Grp 2 Member C

A. Need for a global microbiome effort via standardize interdisciplinary administration[1]
- **Resolving global hunger requires multidisciplinary collaborative groups with a standardize administrative framework**
  - Holistic understanding of the role of Earth's microbiome
  - Common goal: Using Earth's microbiome to resolve global hunger
- **Unified Microbiome Initiative (UMI) and International Microbiome Initiative (IMI)**
  - Collaborative effort among top scientists from public and private agencies and foundations to research and develop technical solutions
  - Develop a framework that standardize the sharing of technical expertise, research information and funding across borders and disciplines
  - Bring cohesion to the multitude of microbiome initiatives
- **Rationale behind the UMI and possible IMI effort**
  - Overcoming disciplinary silos – Individual compartmentalization of scientific information within the discipline field.
    - Fragmentation of life-sciences field
    - Lack of coordination efforts among various microbiome research endeavours
    - Current global initiatives generate vast amount of data that are not easily comparable and lack consistency in methodologies to comprehend.
- **Some possible ways:**
  - Develop an organization - Monitor developments and implement guidelines for the study of microbiomes.
    - The established standards ➔ Facilitate data sharing, analysis of crucial data and intellectual property.
  - Prioritize and develop unified research agenda
    - The goal of enabling comparative analyses that starts from local geographically areas to global scales worldwide.
  - Develop new research tools and methodologies
    - Facilitate and identify new cross-disciplinary ways for microbiome studies.
    - In-depth access to the availability of research data and chart possible new directions, which can be a potential solution in the future.
  - Establish platforms for proper discussion and exchange of research information within and between countries.
  - Conferences and research seminary meetings
  - Development scholarly programmes
    - Training the next generation of microbiome researchers, and the establishment of outreach projects to educate and engage the general public.

Figure 3. Students using the discussion forum to contribute insights into complex problems from their respective disciplinary perspectives.

Similarly, Group 2 outlines the problem and suggests how their respective disciplines would be relevant, e.g. synthetic biology for engineering microbes, and chemistry for appreciating nitrogen fixation and the bioavailability of elements in soil (Figure 3). In reiterating an earlier point made by the lecturer regarding the need to overcome disciplinary silos, they demonstrate that they understand that their assigned SDG of "Zero Hunger" is sufficiently complex to necessitate an interdisciplinary approach where they must work towards integration rather than fragmentation. They correctly argue that the interdisciplinary nature of microbiome studies necessitates the development of new research tools and methodologies, which would involve the integration of scientific and engineering knowledge.

Based on certain key themes (i.e. state research question, recognise that the problem is complex, identify relevant disciplines, integrate disciplinary insights, and collaborate) that have emerged from their forum discussion, it is evident that both groups understood the definition of interdisciplinarity and applied the Broad Model successfully. The Model and the forum function synergistically to help students think and act in an interdisciplinary way. Consistent with Repko's (2008, p. 44) definition of an interdisciplinarian, our students have successfully coordinated their group discussions and integrated group members' inputs. Applying the Model in their discussions had a positive influence on their final presentations (as will be summarised later).

Forum discussions indicated that students were actively utilising the Broad Model. These discussions yielded insights that they used in their presentations and generated solutions that reflected a better understanding of interdisciplinarity. This observation is in line with what many studies have found, i.e. that asynchronous communication via forums can be useful in promoting critical thinking and collaboration, as discussions are more "thoughtful, reasoned, and draw evidence from other sources" (Abrams, 2005; Meyer, 2003, p. 6). Online forums can serve as a permanent record and help students organise their thoughts which, in turn, aids reflection and critical thinking (Garrison & Vaughan, 2008). This is especially useful in interdisciplinary learning, where students must grapple with many new terminologies and integrate insights from a wider range of sources. For instance, forum threads and headers could be used to keep track of the topic at hand. As is evident from our students' discussions and presentations, such collaboration, when coupled with the Broad Model, can lead to the production of meaningful interdisciplinary solutions amongst students.

Most students reported that one of their greatest takeaways from their forum discussions and interactions with their presentation group-mates was learning how to communicate and collaborate with people of other disciplines more effectively, given that they had to explain difficult and unfamiliar terminologies and concepts in their respective fields to one another. They suggested how this experience would help them in their careers, namely that within academia they might need to collaborate with people from different disciplines, whereas outside academia it would be crucially important for them to communicate technical knowledge with their layperson colleagues.

However, even though students used the forums extensively (we did not mandate a minimum number of posts each student should contribute), only a minority of students (35.8%; see Table 1) indicated on the survey that they liked using the forums. Interviews revealed that this was more to do with the technical deficiencies of our LMS which resulted in, for example, students posting over each other. Furthermore, they said that the discussion forum interface in the LMS was not user-friendly because it was difficult to view and keep track of posts and respond in a timely manner. As a result, they preferred other online platforms such as Google Docs, and/or instant messaging services such as WhatsApp to conduct discussions. Overall, while the discussion platform itself could be improved to further stimulate students' critical thinking, merely having such a platform and incentivising students to use it also serves to create an environment which fosters interdisciplinary collaboration.

Table 1
Detailed breakdown of survey results described in the paper.

#	Question	Strongly Disagree (%)	Disagree (%)	Agree (%)	Strongly Agree (%)	Did not answer question (%)
31	I liked having discussions on the discussion forum	35.7	28.6	35.7	0.00	0
34	The instructor's feedback on the presentation outline was helpful	0.00	10.7	57.1	32.1	0
35	The instructor's feedback on the presentation outline helped guide us toward more interdisciplinary thinking	0.00	14.3	64.3	21.4	0
43	My group gave feedback to our partner group seriously	0.00	0.00	42.9	57.1	0
44	The feedback provided by the other group prior to the group presentations was helpful	3.6	3.6	75.00	17.9	0
45	Having partner groups review each other's work was helpful	3.6	7.1	60.7	28.6	0
46	My group reflected on how to make our project more interdisciplinary after giving feedback to our partner group	0.00	17.9	60.7	21.4	0
47	My group modified our project based on our partner group's feedback	3.6	3.6	78.6	10.7	3.57

FEEDBACK AND PRESENTATIONS

Instructor and peer feedback

Scaffolding online discussions is an important activity that instructors perform to improve students' experiences in a blended learning environment. Students report higher levels of connectedness and learning when online instructors provide facilitation in online environments, although a careful balance must be struck as too much instructor intervention leads to less student participation (Garrison & Vaughan, 2008; Shea et al., 2006). In addition to discussion forums, our blended learning format included an online instructor and peer feedback exercise. Apart from monitoring and posting on individual groups' discussion boards, the instructor provided general feedback on student's presentation outlines to the entire class in the middle of the week, reminding them about how to better utilise interdisciplinary understandings to propose better solutions (Fig. 4). This type of feedback allowed the instructor to reiterate the need to rely on the Broad Model.

Dear class,

I've looked through your outlines and given some feedback on them. They are generally fine, with a clear and logical structure.

As you continue refining your presentations, here are some points you might want to take note of:

The most important thing we want to see is an exchange of interdisciplinary perspectives. That means either approaching the problem and proposing several solutions from different perspectives (biology, engineering etc.) or just one solution, but with input from each perspective. The most important thing is that your presentations consider and show how different members' perspectives have been considered to tackle the idea. For example, "Our solution is XXX. From a biological standpoint, this would work because... It is also feasible from an engineering standpoint too because...However, from a ________ perspective, it might not work/there might be concerns with...Yet..."
Since you are scientists, **you do not have to**, but you might also consider social/political concerns arising from your solution. Of course, many of you have also done the GS6001 module on ethics, so that knowledge could be applied here too.

Thus, a bit of technical detail is required but not too much! We need you to have one (or more) clear and explicit take-home message (s) – which is still lacking for many groups – and explain and defend those ideas based on research and your own areas of expertise. As noted in lecture, this is a very important part of doing PhD projects. If you use case studies, you should show how they are relevant to your proposals and what you can learn from them.

Keep up the effort and remember to update and upload a copy of your revised presentation outline in the Workbin on Friday (See lesson plan for details). It should be sufficiently detailed and coherent for your partner group to give constructive feedback.

Do feel free to ask me if you have any queries or need clarification!

Figure 4. Instructor provides feedback to the class halfway through the instructional week

The above instructor feedback concludes with a reminder to revise the presentation outlines in time for peer feedback from a "partner" group. As mentioned in an earlier section, each of the 3 SDGs was pre-assigned to two groups known as "partner groups". The purpose of this allocation was to allow the respective partner groups to exchange peer feedback on their presentation outlines at the end of the week, and to exchange questions for the question-and-answer (Q&A) segment during the F2F group presentations. We did not specify what kind of feedback was to be given. However, most groups commented on the interdisciplinary nature of the partner group's solution, the logical flow of the presentation, and the limitations of the approach. The feedback given to their partner groups suggests that students understood and were actively using the ideas of interdisciplinarity as they also gave their suggestions based on the Broad Model.

For example, when commenting on Group 2's presentation outline, Group 1 felt that "the problem-solution link and presentation seem appropriate but solutions seem to mainly come from a biological perspective. Perhaps inclusion of multidisciplinary considerations may be valuable".

Meanwhile, Group 3 felt that Group 4 had presented a clear rationale for harnessing the microbiome to achieve their SDG and had explicitly indicated that their approach was interdisciplinary (involving disciplines like biology and engineering). Group 3 noted that Group 4 appreciated the complexity of the problem, and the latter had referred extensively to literature from various disciplines. In their feedback to Group 3, Group 4 said that the outline was "clear but would benefit from greater elaboration". Specifically, Group 4 said that Group 3 needed to clarify which disciplines (scientific or otherwise) need to work together for the proposed solutions to be successfully implemented. Collectively, these remarks show that students had a good grasp of interdisciplinarity and that they acted upon this feedback when preparing their respective group presentations.

Most students agreed that the instructor's feedback on the presentation outline was helpful (89.3%), and that the instructor's feedback on the presentation outline guided them towards more interdisciplinary thinking (85.7%). The instructor's feedback also served as an appraisal of the students' current performance. That most of the students in this study found instructor feedback useful is reassuring, and suggests that the instructor feedback in the form of comments and questions was effective. The benefits of teacher feedback have been well-studied, especially in helping to improve student understanding (Kluger & DeNisi, 1998; Ponte et al., 2009), but it was only recently that instructor feedback on online platforms was investigated. As reported by Guo et al. (2014), good instructor feedback improved online cognitive engagement.

In line with Chin and Osborne's (2008) recommendation that students need to be prodded to ask good questions so as to promote higher-order thinking, we required students to provide both critical comments and questions in their peer feedback. All students welcomed the peer feedback, took the feedback-giving exercise seriously, and felt that their own group had provided their partner group with good questions. 92.9% found the partner group questions helpful. Most students also said that their group had modified their own presentation based on feedback received from the partner group (89.3%), and that having the partner groups review each other's work was helpful (89.2%). 82.1% agreed that their own group reflected on how to make their project more interdisciplinary after giving feedback to their partner group.

Giving peer feedback is a common way of promoting student engagement and improving learning outcomes (Gikandi & Morrow, 2016). Receiving peer feedback allows students to justify and explain their positions, rethink them, or re-frame problems entirely to help in problem solving (Kim & Ryu, 2013). As Lu and Law (2012) posit, the act of giving peer feedback has a greater impact on learning outcomes than merely receiving feedback, supporting the idea that students do think about their own work in the process. This peer feedback exercise had the added advantage of encouraging spontaneous questions during the face-to-face Q&A, which was a vast improvement from the traditional format where hardly any students would ask questions. Giving feedback to their group members online, giving feedback to other groups, and then improving upon received feedback is thus a form of "social reflection" and "articulation" (Herrington & Herrington, 2006), which are important for making learning authentic and collaboratively creating knowledge.

STUDENT PRESENTATIONS

In their presentations, students were ultimately able to integrate ideas from their forum discussions and feedback given by the instructor and their peers, showing a marked improvement from the outlines they had initially submitted. They generated innovative solutions and more explicitly discussed how various disciplines might contribute to making these solutions more workable in real life. For instance, Group 1 presented out-of-the-box thinking through a creative manipulation of bacterial communication in biofilms, drawing on computational science, biology, chemistry and physics. They concluded the presentation by presenting the very powerful idea that nature is "interdisciplinary" and that it should be approached it in an interdisciplinary manner.

Similarly, Group 2 explicitly integrated ideas from engineering, biological, and chemical perspectives to suggest how the microbiome could improve agriculture and nutrition to alleviate hunger, the limitations of these solutions, and new research methods needed to further study this problem.

Given our limited F2F instructional time, the online discussion forum gave students a platform to continue their discussions and build on each other's ideas. From their posts, it was clear that the Broad Model served as a useful discussion scaffold as they integrated insights from the model into their discussions and even gave feedback to other groups using it. The instructor could also monitor these discussions and intervene when necessary, prompting students to elaborate on good ideas, or giving them suggestions of other things to include.

Collectively, our findings suggest that blended learning combined with the Broad Model framework helped to foster collaboration, and ultimately helped students achieve a better understanding of interdisciplinarity, which was reflected in their presentations.

CONCLUSIONS AND FUTURE DIRECTIONS

As this exploratory study shows, the interdisciplinary framework combined with blended learning promoted collaboration amongst our PhD students. Making the interdisciplinary process explicit via the definition of interdisciplinarity as well as the Broad Model guided students towards achieving the learning objectives for the topic "Microbiomes and Sustainability". Our use of the Broad Model to guide students in their interdisciplinary work is similar to an approach adopted by Stamp et al (2015), who conducted workshops as part of their interdisciplinary research programme to train novice undergraduates and especially their graduate mentors for interdisciplinary research with a particular focus on their readiness for collaboration. The workshops' interdisciplinary research module was based on Allen Repko's (2008) *Interdisciplinary Research: Process and Theory*, which advocates the Broad Model as a process for facilitating effective communication across disciplines. Furthermore, the authors based the workshops' activities on research problems identified in current events media, such as projects funded by the Bill and Melinda Gates Foundation's Grand Challenges Explorations. These projects address world health problems, which typically necessitate a broad interdisciplinary approach. Recognising the need for educational models that foster interdisciplinarity, others like Bosque-Perez et al. (2016) have devised a model that, inter alia, identifies integrated research questions combining students' disciplines, and features coursework that explores the theoretical underpinnings of interdisciplinarity in order to achieve integrated proposals that address these questions. Similar to the above examples, "Microbiomes and Sustainability" is a complex and current topic which requires an interdisciplinary approach which would require students to combine their disciplines to devise potential solutions. As students were able to handle the topic "Microbiomes and Sustainability" well, we intend to include it in future semesters.

Our findings suggest that blended learning is an effective way of promoting collaboration in the ISE module's unique interdisciplinary setting. To make the discussion forums more effective, we suggest providing students with questions that they would answer F2F prior to engaging each other online. Building on ideas expressed in a recent Reflection on Practice, we will design questions that address epistemological and metaphysical issues relevant to interdisciplinary collaboration (Rashid, 2019). These questions, based on the "Toolbox Project" originally developed at the University of Idaho (Eigenbrode et al., 2007), would prompt students of different disciplines to express their views on the philosophical aspects of research, which we believe is a stepping stone to achieving interdisciplinarity. As part of their effort to impart interdisciplinary sustainability science teamwork skills to graduate students using in-person and web-based interactions, Knowlton et al (2014) deployed three out of six Toolbox question sets in class. Similarly, Schmidt et al (2012) observed that epistemological, communication, and methodological barriers impede interdisciplinary boundary-crossing and thus limit researchers' abilities to collaborate effectively. They suggest that students could use the Toolbox to teach other students about their disciplines and facilitate communication. We will thus design three to four questions based on the original Toolbox questions. Furthermore, given the fact that blended learning could also include online video lectures, we will consider introducing students to the rationale behind the Toolbox project through "micro-lectures" that they will have to watch prior to a F2F discussion of their answers in class.

Overall, our findings suggest that the interdisciplinary framework and blended learning approach that we introduced were useful in promoting interdisciplinary collaboration amongst our students. We believe that our approach represents an important contribution to interdisciplinary educational reform at the doctoral level. The overall goal of such reform would be to train students to be thinkers rather than just specialists (Bosch & Casadevall, 2017). These and other authors have suggested putting the "Philosophy" back into "Doctor of Philosophy" (Blachowicz, 2009; Grayson, 2006; Grune-Yanoff & Grune-Yanoff, 2014; Prather et al., 2009), which inspires us to reform our own curriculum.

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ENDNOTE

1. These authors launched a pilot course in which students would (1) review disciplinary and interdisciplinary scientific literature, (2) frame interdisciplinary sustainability science research questions and suggest experimental designs, (3) communicate oral and written proposals, and (4) work successfully in international interdisciplinary science teams.

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APPENDIX 1. THE INTEGRATED MODEL OF THE INTERDISCIPLINARY RESEARCH PROCESS ("BROAD" MODEL)

APPENDIX 2. FULL SURVEY QUESTIONNAIRE