Nature-Inspired Chemical Engineering: Course Development in an Emerging Research Area

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Nature Inspired Chemical Engineering: Course Development in an Emerging Research Area

Abstract

In 2013, University College London was awarded an EPSRC (United Kingdom's Engineering and Physical Sciences Research Council) "Frontier Engineering" Grant to form a multi-disciplinary *Centre for Nature Inspired Engineering*. The overarching vision of the center is to use *nature* as a guiding platform to seek potentially transformative solutions to engineering grand challenges, such as sustainable energy and clean water. Beyond biomimicry, this nature-inspired approach seeks to reveal fundamental mechanisms in the natural world that underlie desirable properties such as scalability, efficiency or robustness, and can be applied in a broader context to solve similar problems in engineering.

To complement the new research center, a new senior undergraduate and Master's level elective course on *Nature Inspired Chemical Engineering* was designed, developed, and taught by Professor Marc-Olivier Coppens of University College London and Professor Daniel Lepek of The Cooper Union. One of the main learning objectives of the course was to stimulate creative thought in leveraging natural phenomena to solve chemical engineering problems. This was achieved by using a variety of active learning and pedagogical techniques such as, annotated textbook readings of current journal publications, oral presentations highlighting the balance between nature and technology, laboratory demonstrations, and a semester-long group project motivated by student interest in nature and chemical engineering.

In this paper, the opportunities and challenges associated with developing a new course in an emerging multidisciplinary research area will be addressed. In addition, suggestions for best practices in course development will be provided for instructors who seek to develop similar new research-based elective courses.

Background

In 2014, a new graduate-level course intended for Master's students on *Nature Inspired Chemical Engineering* was conceptually initiated and submitted for approval at University College London. One of the main reasons to offer a course on this unique topic was to develop strong synergies with a recently founded interdisciplinary research center. During the previous year, University College London was awarded an EPSRC (United Kingdom's Engineering and Physical Sciences Research Council) "Frontier Engineering" Grant to form a multi-disciplinary *Centre for Nature Inspired Engineering*. This grant was spearheaded by Professor Marc-Olivier Coppens, who recently left the United States to become Head of the Department of Chemical Engineering at University College London. Professor Coppens's research encompasses a wide range of areas including diffusion, catalysis, fluidization, novel functional materials for reaction engineering and separations, and fractals. A common theme that runs through his work is the influence of nature, particularly as a driving force or initiator to solve problems in chemical engineering. During the time at which this course was being conceptualized, Professor Daniel Lepek of The Cooper Union was offered the opportunity to spend part of his sabbatical at

University College London. Although Professor Lepek's research interests are aligned with those of the research center, he has also been recently active with researching new technological approaches to enhance student learning. These new approaches were adopted during the course, while leveraging Professor Coppens's experience in transforming the capstone Chemical Process Design course at his former US university, and a project-based course on fractals in chemical engineering taught in the USA and the Netherlands. Working together, this new elective course provided students with an introduction to the emerging research area of *Nature Inspired Chemical Engineering*, leveraged new technologies to help improve the learning process, and prepared them for applications in the future workplace.

Centre for Nature-Inspired Engineering

The overarching vision of the *Centre for Nature-Inspired Engineering* is to use *nature* as a guiding platform to seek potentially transformative solutions to engineering grand challenges, such as sustainable energy, clean water, and scalable manufacturing.   Sustainable energy and increased energy efficiency, clean water, atom-selective and robust chemical transformations – these are some of the grand challenges requiring breakthrough solutions that are economically and environmentally acceptable. Despite tremendous progress in molecular and nanoscience, there are gaps in translating this progress, through engineering, to macroscopic scales. The *Centre for Nature-Inspired Engineering* looks for guidance from nature to fill in these gaps to solve some of the world's engineering grand challenges. It involves researchers from a broad range of fields, including (bio-) chemical engineering, mechanical engineering, chemistry, computer science, and architecture.

The research portfolio of the *Center for Nature Inspired Engineering* is focused around three "themes" which correspond to three fundamental mechanisms. These three "themes" are: (T1) hierarchical transport networks, (T2) force balancing, and (T3) dynamic self-organization. The following diagram (Figure 1) illustrates the nature inspired approach and the three "themes":

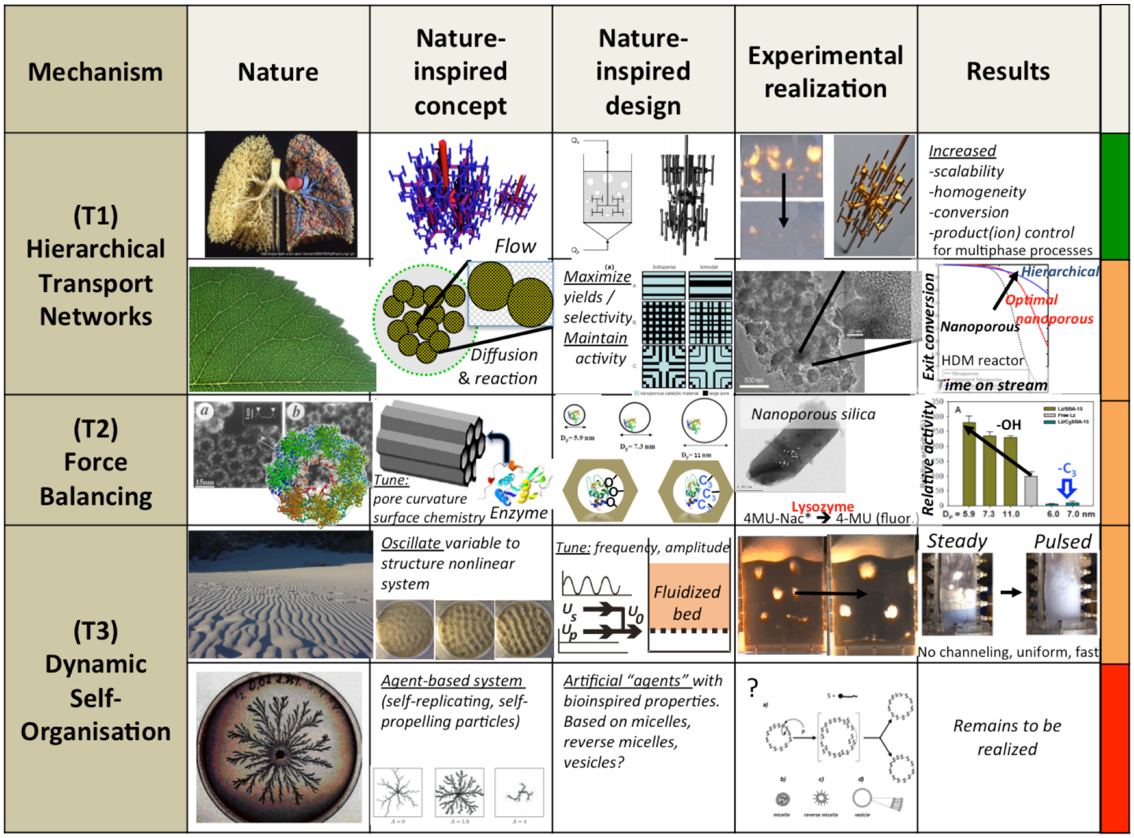

Figure 1 - Themes of the Center for Nature Inspired Engineering [1]

The core of this research center is based in the Department of Chemical Engineering at University College London and is heavily aligned with the individual research group of Professor Marc-Olivier Coppens.

Nature-Inspired Chemical Engineering

Nature Inspired Chemical Engineering vs. Biomimicry

Nature Inspired Chemical Engineering is a new emerging research area of chemical engineering that seeks guidance from nature, using *fundamental* mechanisms to solve chemical engineering problems. Although the literature would suggest that engineers have sought inspiration for over hundreds of years, the nature-inspired approach is unique in that it seeks to understand, and apply in a broad sense, the fundamental mechanisms involved, while explicitly accounting for the usually quite different context and constraints of the technological application. This is inherently different from biomimicry, which has frequently been used in the past to develop new products and processes.

According to the Biomimicry Institute, **"**Biomimicry is an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies**.** The goal is to create products, processes, and policies—new ways of living—that are well-adapted to life on earth over the long haul." [2] Biomimicry differs from the nature-inspired approach in that, in general, it doesn't seek a deeper understanding of the mechanisms; rather it tends to presume that nature's solution is "best" without accounting for the different goals and context of natural and technical issues to address. However, despite its inherent limitations, biomimicry has been used as both a source of technological innovation, and a platform for student motivation in engineering education [3-6]. For example, the specific valve system inspired µMist® spray platform technology was developed based on the hot venom spraying behavior of the bombardier beetle [7].

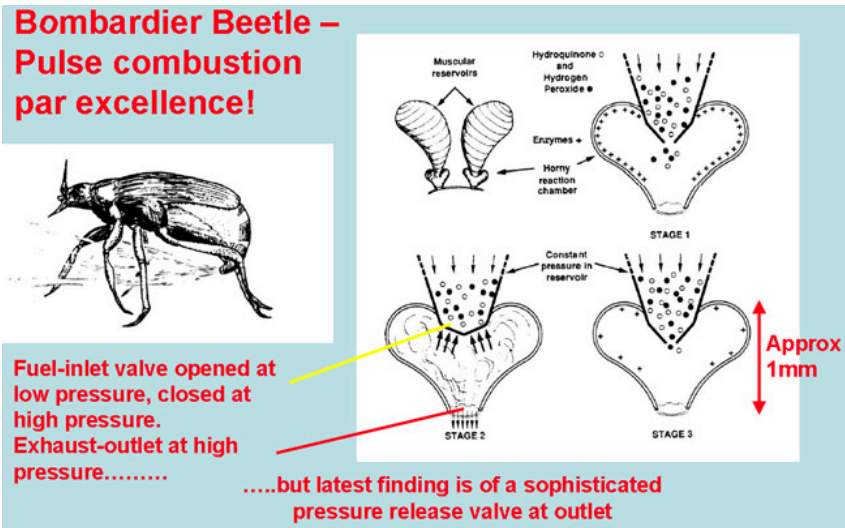

Figure 2 - Combustion properties of the Bombardier beetle [7]

One of the primary goals in this course was to motivate the students to seek a deeper understanding of fundamental mechanisms in nature, not just ways to "emulate" naturally-occurring phenomena. This was achieved by requiring the students to link, if possible, their work to the three major themes of the *Centre for Nature Inspired Engineering*. For example, if a student was developing a new material based on the unique properties of spider silk, we would motivate the student to look past the fundamental materials science properties, and to seek inspiration from the molecular structure and force balancing mechanisms which cause the unique properties. Likewise, if a student was trying to developing a material to clean up oil spills based on oil-eating bacteria, we would motivate the student to find out what are the reactions and mechanisms behind these unique digestive properties of bacteria, and how can they be replicated and scaled-up to produce new materials.

Themes of the Centre for Nature Inspired Engineering

The three major themes of the *Centre for Nature Inspired Engineering* are (T1) hierarchical transport networks, (T2) force balancing, and (T3) dynamic self-organization. They are illustrated in Figure 1.

Hierarchical transport networks (T1) bridge and preserve the common functional phenomena observed across microscopic and macroscopic length scales. Three examples of hierarchical transport networks observed in nature are those found in trees, leaves, and lungs.

These naturally occurring objects exhibit common branching phenomena, which are, in part, self-similar fractals (upper levels) and are uniformly connected (lower levels). These structures are not arbitrary, but related to scalability and efficiency with different physical transport phenomena (convection, diffusion, capillary flows) dominating at different length scales. Currently, the *Centre for Nature Inspired Engineering* is developing new reactors, fuel cells, and hierarchically structured porous materials based on these unique hierarchical transport systems with optimal properties.

Force balancing (T2) refers to the balanced use of fundamental (e.g., electrostatic, polarization) forces and geometrical confinement (as in protein channels in cell membranes and chaperones that assist in protein folding). Currently the *Centre for Nature Inspired Engineering* is developing new nanoporous catalysts and nature-inspired biomembranes for water desalination and bio-separations based on this theme. In the course, we have extended the theme of force balancing to include all forces including gravitational forces, as in mechanical and construction engineering.

Dynamic self-organization (T3) employs the use of fluctuations to induce structure (as in natural pattern formation and selection) and the emergence of structure through collective phenomena (e.g., bacterial communities). Two examples include the formation of patterns formed on sandy beaches and bacterial communities. These inspire methods to structure fluidized bed reactors, and novel self-healing materials, respectively.

The thematic nature-inspired chemical engineering methodology is illustrated in Figure 1, by means of a few examples that show the systematic path from the natural model to the nature-inspired concept, the design, and the ultimate realization of a solution to an outstanding technological problem.

Course Outline

Developing the course

In developing this course, one of the questions that the authors tried to answer was, "*how does one create a course in an emerging research area?*" This was a challenge, particularly since no textbook or general reference is available for this topic. In addition, the range of course topics is quite varied across chemical engineering (e.g., fluid-particle systems, catalysis, fuel cells) and mathematical topics (e.g., fractals and nonlinear systems). Another challenge in developing the course was to determine the balance of the chemical engineering and mathematical prerequisites. Although this was a senior (fourth-year undergraduate) and graduate-level Master's chemical engineering course, not all students had the same undergraduate background.

Since both instructors were initially located on different continents, planning meetings by Skype occurred in the year prior to offering the course, and course approval was obtained by Professor Coppens at University College London. Once Professor Lepek was on campus at University College London, in-depth planning meetings occurred three weeks before the term began.

Overall Goal

In developing this course, we tried to develop an "overall goal", or perhaps a general "takeaway" that the students would have after completing the course. The following language was officially formulated (as required by University College London) to describe this goal:

> *"This module aims to grow an understanding of ways to learn from solutions adopted by* ***nature*** *to solve similar issues in* ***chemical engineering problems****. This is done by distilling the fundamental causes behind desirable features in the model* ***natural system****, and applying these to the* ***technological system****. The modules aims to stimulate creative thought, and to engage students in coming up with innovative solutions by using the nature-inspired chemical engineering "toolbox" with a fresh pair of eyes."*

In the UK, a "module" refers to a typical "course" in the U.S. As can be seen from the above language, not only did we want our students to learn from nature and solve problems, but we wanted to stimulate creativity and engagement. When developing the coursework and project for this course, we always took into account how students would be stimulated, or inspired, by nature. Furthermore, we sought ways to engage the students in the material through varied methods of delivering course content.

Student Learning Outcomes

After determining the overall goal and theme of the course, we proposed five major student learning outcomes that the students would achieve upon completion of the course. The student learning outcomes were the following.

On successfully completing the module, the students will:

1. Look at nature, and the balance between nature and technology, in a different (more advanced) way
2. Learn the fundamentals and opportunities of the nature-inspired chemical engineering (NICE) approach
3. Apply fundamental principles, borrowed from natural systems to chemical engineering problems
4. Recognize situations where a NICE approach might bring up a new, more performing solution
5. Employ the NICE toolbox to solve engineering problems

These student learning outcomes were linked to the Engineering 2010 Subject Benchmark Statement of the Quality Assurance Agency for Higher Education (QAA) in the UK [8].

Topics Covered and Class Structure

The topics that were covered in the course ranged from traditional chemical engineering topics (e.g., fluidization, catalysis) to newer emerging chemical engineering topics (e.g., nano-confinement, fuel cells) and mathematical topics such as fractals. The course started with a general introduction to the *Nature Inspired Chemical Engineering* (NICE) approach and how nature can provide inspiration to scientists, engineers, and architects looking for new solutions to long-standing technical problems. During the next week, laboratory tours and demonstrations were given to the students by members of Professor Coppens's research group to highlight the topics in the course as well as the instrumentation used to study these topics. Starting with the fourth week of classes, the following series of topics were taught by lecture:

- *Multiscale, hierarchical systems*
- *Fractals*
- *Applications to Fluidization and Fluid-Particle Systems*
- *Applications to Catalysis and Hierarchically Structured Catalysts*
- *Nano-confinement*
- *Fuel Cell Engineering (Fundamentals and Applications)*
- *Separations – membranes*

In addition to lectures, individual sessions were scheduled between students and Professor Lepek to formulate and refine group projects that continued throughout the term. When teaching the topic of fractals, coursework was assigned to practice the basics of fractals, with group discussions with Professor Coppens to make students feel comfortable with the basics of fractal geometry, to the extent relevant to the course.

Textbooks

One of the challenges associated with teaching a course in a new emerging research area is that, frequently, no textbook or general reference is available. The instructors felt that it was necessary to recommend textbooks on fractals and their applications rather than chemical engineering texts, since most of the students had backgrounds in chemical engineering. The following supplemental texts on fractals were recommended:

1. B.B. Mandelbrot, The Fractal Geometry of Nature, Updated and augmented ed. Freeman, San Francisco (1983) [9]
2. T. Vicsek, Fractal Growth Phenomena, World Scientific, 2 Ed., Singapore (1992) [10]
3. J. Feder, Fractals, Springer, New York (1988) [11]

In order to introduce students to the relevant new chemical engineering material, the students were required to read and comment on recent journal publications using the software Perusall.

Assignments and Assessment

Perusall

Perusall is a relatively new, web-based software package developed by Professor Eric Mazur of Harvard University, one of the key development of the "peer instruction" pedagogical approach. *Perusall* was used as a "platform" for students to read and annotate journal publications. For each course topic, students were required to read the paper online and provide a minimum of five comments for the paper. The following shows an annotated journal article:


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Current Opinion in Chemical Engineering

A nature-inspired approach to reactor and catalysis engineering

Marc-Olivier Coppens

Mechanisms used by biology to solve fundamental problems, such as those related to scalability, efficiency and robustness could guide the design of innovative solutions to similar challenges in chemical engineering. Complementing progress in bioinspired chemistry and materials science, we identify three methodologies as the backbone of nature-inspired reactor and catalysis engineering. First, biology often uses hierarchical networks to bridge scales and facilitate transport, leading to broadly scalable solutions that are robust, highly efficient, or both. Second, nano-confinement with carefully balanced forces at multiple scales creates structured environments with superior catalytic performance. Finally, nature employs dynamics to form synergistic and adaptable organizations from simple components. While common in nature, such mechanisms are only sporadically applied technologically in a purposeful manner. Nature-inspired chemical engineering shows great potential to innovate reactor and catalysis engineering, when using a fundamentally rooted approach, adapted to the specific context of chemical engineering processes, rather than mimicry.

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This review comes from a themed issue on **Reaction engineering and catalysis**

Edited by **Theodore T Tsotsis**

For a complete overview see the Issue and the Editorial

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Introduction

Nature-inspired engineering researches the fundamental mechanism underlying a desired property or function in nature, most often in biology, and applies this mechanism in a technological context. In the context of chemical engineering, we call this approach: *nature-inspired chemical engineering* (NICE) [1].

Application of biological mechanisms to a non-physiological context in reaction engineering requires adaptations, because the relevant time scales and available building blocks are different. Also, we are able to manipulate parameters such as temperature and pressure, which are much less tunable in biology. Hence, like in an abstract portrait, essential aspects of the subject are preserved, but not literally, emphasizing those features that serve a desired purpose. Such features underpin the rational design of an artificial structure that uses the same fundamental mechanism as the natural system. The ultimate implementation is assisted by theory and experimentation. NICE aims to innovate, guided by nature, but it does not mimic nature, and should be applied in the right context.

Emphasizing reactor and catalysis engineering, we illustrate how mechanisms used in biology to satisfy complicated requirements, essential to life, are adapted to guide innovative solutions to similar challenges in chemical engineering. These mechanisms include: (1) use of optimized, *hierarchical networks* to bridge scales, minimize transport limitations, and realize efficient, scalable solutions; (2) careful *balancing of forces* at one or more scales to achieve superior performance, for example, in terms of yield and selectivity; (3) emergence of complex functions from simple components, using *dynamics as an organizing mechanism*. Figure 1 presents an overview.

In this way, NICE complements an ongoing revolution in bioinspired chemistry and materials science [2••,3••,4–6], which already sees applications in, for example, enzyme-mimics and antibody-mimics for catalysis [7–10] and in artificial photosynthesis [11•,12•,13–15]. These applications implement essential mechanistic steps of the biological model system at molecular and supramolecular scales. Hierarchically structured bionanocomposites have superior properties by synergy, unmatched by their individual components, inspiring novel material designs.

As we now illustrate, nature has more to offer to reaction engineering when considering larger length scales and the time domain. In addition, the manipulation of force balances as an organizing mechanism merges bioinspired chemistry, chemical and materials engineering.

Hierarchical transport networks

Transport is crucial to living systems, and to reaction engineering alike. Trees and mammalian physiological networks share common architectural traits that endow them with vital properties. The vascular and respiratory networks have a branched, hierarchical architecture that is *fractal* between macroscopic and mesoscopic length scales, having features that look similar under repeated magnification [16••,17]. At those scales, *convective flow* is the dominating transport mechanism and the channel walls are impermeable. On the contrary, channels are

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Figure 3 - Example of Perusall used in annotating a paper.

Although it may be hard to view, the highlighted text in color above in Figure 3, refer to text that the students have provided additional comments or questions.

In addition to requiring student annotations, frequently the professors would pose a question on a particular paper. The following figure shows a question posed by one of the professors and the corresponding student comments:

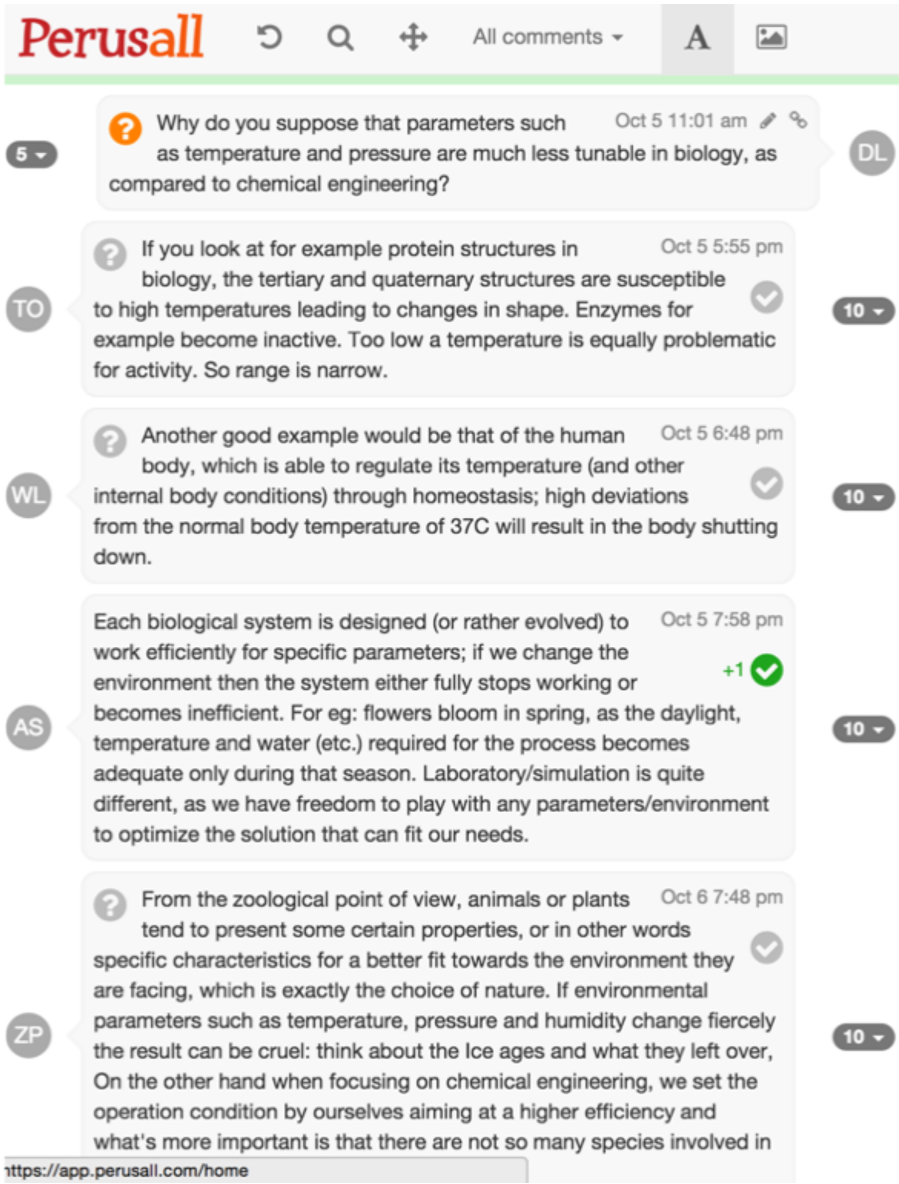

Figure 4 - Comments thread on Perusall

One of the most unique aspects of *Perusall* is that it can automatically grade the quality of the comments based on a machine-learning algorithm. The algorithm is based on the quality and timeliness of the comments. Another unique aspect of *Perusall* is that it generates a confusion report when at least 20 questions have been asked regarding the paper.

Prior to each lecture, the assigned paper on *Perusall* was scanned for all questions and those questions were brought to class and answered and discussed by the professors. Based on our interactions with students, we found that they preferred their questions to be answered in class instead of left unanswered on *Perusall*.

Overall, seven journal publications were assigned to be read and annotated using *Perusall* [1, 12-17]. Some were assigned before and others after the topic of lecture.

We found that the students liked the interactive approach, although it challenged them quite considerably. It helped them to be better prepared on topics they were less familiar with and be immersed in the newest research on the topic, illustrating the relevance of it, and setting the scene for future research. The time required for students to prepare, and the grading proved to be the more difficult aspects of this approach, but it was clear how the level of understanding and engagement was unusually high, as witnessed in class and project discussions.

Coursework

In order to provide balance to the students in terms of course load and assessment, two major courseworks (i.e., homeworks) were assigned. The first coursework was based on the introduction of the course and contained two major questions. The first question required the students to identify a chemical engineering problem that would potentially benefit from a nature inspired solution using the three "themes" of the course (i.e. hierarchical transport systems, force balancing, dynamic self-organization). The second question required the students to think how the principles of *Nature Inspired Chemical Engineering* could be used to solve the seven Engineering Grand Challenges, as recently identified by the Engineering and Physical Sciences Research Council (EPSCR), the funding agency of the *Centre of Nature Inspired Engineering* grant. The following are the engineering grand challenges that the students had to link to the course:

- Risk and resilience in a connected world
- Controlling cell behavior
- Engineering from atoms to applications
- Bespoke engineering
- Big data for engineering futures
- Suprastructures - integrating resource structures under constraint
- Engineering at the heart of public decision making

NICE Course Final Project

When developing the course, we felt it was critical to have the students work on their own nature-inspired chemical engineering project. We determined that it would be best to have the project run throughout the entire term and to aid the students with *project milestones* that had to be completed at certain deadlines. This insight was gained from applying similarly successful approaches in the past when both professors previously taught intense project-based courses, such as chemical process design.

During the third week of class (after the students received the introduction to the NICE approach), students were required to form groups of 2-3 and to seek inspiration from nature. In order to accomplish this, a "project synthesis" assignment was assigned that required the students to go out into nature, and to link visually-observed phenomena to a chemical engineering problem. The groups were required to submit a 2-3 slide presentation and give a five minute presentation to the class on their topic. Although these presentations were not required to be their final chosen topic, they at least provided the students with an approach to synthesize a project and identify a problem within the context of nature.

Approximately three weeks after the synthesis assignments, the groups were required to submit a 1-2 page proposal for what they planned to study. As part of their proposal, the following sections were required:

- The problem - what is the problem that you want to solve? Why do you think a nature-inspired approach will work, or perhaps be better than a traditional approach?
- Inspiration from nature - how is your project inspired by nature? How is it different from biomimicry?
- Environment - in what natural environment does your project occur (or is inspired by)?
- Geometry/structure - is there a unique geometry (e.g. fractals) or structure to your system?
- Chemical engineering - what are the chemical engineering principles? What are the applications to chemical engineering?
- Milestones - what are the milestones that you must achieve to solve your problem?
- Propose some tentative deadlines as well.
- References - include at least three (3) scholarly references to support your project.

Approximately three week after these project proposals were due, the groups were required to prepare a project summary of their work so far in the form a 8-10 minute presentation. In between these assignments, the students had a “reading week” free of class that they could use to prepare for this project. For the project summary, a list of similar sections were required, although we stressed a new section on feasibility, as we wanted our students to start thinking of the limitation and achievability of their design. Their project summary had to contain the following sections (and information):

- The problem - what is the problem that you want to solve? Why do you think a nature-inspired approach will work, or perhaps be better than a traditional approach?
- Inspiration from nature - how is your project inspired by nature? How is it different from biomimicry? Which principle of nature-inspired engineering drives the work behind your project?
- Environment - in what natural environment does your project occur (or is inspired by) how does the environment influence the problem?
- Geometry/structure - is there a unique geometry (e.g. fractals) or structure to your system? If so, how will you address the mathematical modeling of your system?
- Chemical engineering - what are the chemical engineering principles? what are the applications to chemical engineering? What models/equations will be required to solve the problem? (Note: although you must include some mathematical modeling based on chemical engineering principles, they don't have to be solved right now).
- Feasibility - how will you measure the feasibility of your nature-inspired approach to solve the problem? Has this problem been solved before? if so, what methodology was used to solve the problem? If not, how will you attempt to determine if your solution is feasible?
- Milestones - what are the milestones that you must achieve to solve your problem? Propose some tentative deadlines as well.
- References - include at least three (3) scholarly references to support your project. For each reference, provide a short summary of its findings and how it's linked to your

project.

When the students gave their presentations on the project summaries, in-depth feedback in the form of written rubric grading and oral suggestions were provided to the groups. In general, and informal atmosphere was established during the class time so that all groups could provide peer feedback and answer any questions pertaining to the project topic.

The final requirement to complete the course project was to submit a final report, written in the form of a grant proposal. The format of a grant proposal was chosen because we felt that the students did not have enough time to properly finalize their group's designs based on the time associated with the class (e.g. 12-13 week term). Therefore, we felt that it would be interesting and thought-provoking for the groups to submit an "Inspiration Grant" to initiate a research collaboration between their group and University College London's *Centre for Nature Inspired Engineering*. This "proposal" would rely heavily on the work that they have achieved so far based on their feasibility studies, and would identify future directions to complete the work. The grant proposal was required to have the following sections:

- Title - what is the title of your project?
- Problem Statement - what is the chemical engineering problem that you are seeking a nature-inspired solution for? Please be as descriptive and complete as possible. Remember that you are seeking funding for your work, so it is important to state the seriousness of your problem and why it's important to solve it!
- Nature-Inspired Approach - explain the general concepts behind your nature-inspired solution (this is to provide a general introduction to your approach - you will go more in-depth later in the proposal). Explain the environment that your project is in or inspired by. Explain if there is a unique geometry or structure to your system. Explain how it is linked to one of the three themes of the Centre for Nature-Inspired Engineering (CNIE).
- Background and Literature Review - provide a thorough background of the problem, complete with sources from a literature review. Also, address previous alternative approaches to solving the problem. Identify and explain the chemical engineering principles underlying your problem and solution method.
- Preliminary Work - in this section, you will discuss your preliminary work in solving the chemical engineering problem, i.e. your feasibility study. Explain your approach to solving the problem using your nature-inspired approach. Include relevant mathematical modeling, calculations, solutions that substantiate your work in solving the problem.
- Future Plans - in this section, discuss what you think are the next steps in sustaining (or completing) this research work. Perhaps provide a timeline (could be up to 3 years) and recommendations for future work. Your future plans must be supported by the previous work that you have accomplished (see previous section – Preliminary Work).
- Impacts - discuss the potential short and long term, social, economic, and environmental impacts of the proposed work (particularly in addressing key engineering challenges)
- References Cited - provide a list of references and sources used (make sure they are properly formatted!)

On the last day of the term, the groups were required to give a 10-15 minute presentation on their project work. We requested that the students focus on the previous work section and the more extensive background and literature review sections. After feedback was immediately given, we allowed the students to spend an additional four weeks working on their project, by which point their "proposal" report had to be submitted.

Assessment

The elements of the course that were used for the assessment include the *Perusall* readings, courseworks, project milestones (including oral presentations), and the final proposal report and presentation. Rubrics were generated for all project milestones, presentations, and reports. Feedback was provided to all students via email or private meetings regarding all assignments in the course. The final raw score for the course was weighted as 70% course (including project milestones) and 30% project (final oral presentation and final proposal report), as was made clear to the students at the state of the course, in agreement with university regulations.

Conclusions

The development of this new course on *Nature Inspired Chemical Engineering* was both challenging and stimulating to the instructors. We sought to engage the students in the course topics by using a variety of methods: lectures, laboratory demonstrations, *Perusall* readings, and multiple oral presentations and feedback sessions. Some of the challenges included balancing the course materials based on the prerequisite knowledge of the students and developing a timeline for the project within the duration of the school term. In addition, although not previously mentioned, we also observed issues with group dynamics and plagiarism, which were addressed as soon as they appeared and discussed with the students.

Offering a new course in an emerging research area is exciting in that a direct link between current research and learning can be clearly established. We found that a few of the student projects strongly capitalized on the strengths of the research center and that some of the projects were worthy of funding. We recommend that faculty consider offering courses in their research areas, despite the fact that references and books may not be available. For example, as an alternative, *Persuall* was found to be an effective tool to transmit course material to the students, and an attractive way to integrate current research and education.

In conclusion, we found that offering this course allowed us, as instructors, to think differently about how to deliver course content and how students learn material in a new emerging research area. For those faculty members considering to offer similar courses, we strongly recommend that multiple planning and course development meetings are established during the prior semester or academic year. We hope that this paper serves as "inspiration" for developing new and exciting courses in emerging research areas.

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