Integrating Multi-scale Approaches and Innovation into Product and Process Design in Chemical Engineering Curricula

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Abstract

Based on our continuous improvement process (as promoted by ABET), the Department of Chemical and Engineering at Universidad de los Andes (UNIANDES) has identified a number of reasons for curriculum change, and has used this stimulus to embark on the task of incorporating multi-scale approaches to Process and Product Design and innovation foundations into our current curriculum. Initially, two courses one at the undergraduate level (e.g., Mid-Program Project) and another at the graduate level (e.g., Advanced Transport Phenomena) have been selected as pilot courses, commencing in 2013.

There are a few issues to resolve, particularly in the extension of the framework to other core courses both at the undergraduate and graduate level but positive feedback have been received so far. The positive reviews of the new approach by renowned members of the Chemical Engineering community both in Colombia and overseas, as well as comments from students and faculty, have been significant and valuable confirmations of our vision.

Introduction

Engineering education is fundamental in enhancing the well-being of people and the environment, and therefore, it is important to take the necessary steps to develop it and enhance it [1]. Finding the most effective ways to teach students and translate that learning into productive skills is an everyday challenge in engineering education. Current research shows that educational quality, more than quantity, has a causal impact on economic growth [2]. The same can be said of innovation, which drives competitiveness [3, 4].

It is well accepted that if developing nations hope to prosper in the global economy and if government leaders expect globalization to foster sustainable development and sustainable poverty reduction, strong STI (Science, Technology and Innovation) capacity building is an absolute necessity. For developing nations, globalization is not a choice, but a reality. To compete in world markets in the so-called knowledge age, developing economies cannot depend only on geography, natural resources or cheap labor. They can only flourish on brainpower, organization, and innovation. Agricultural based economies --as ours-- are severely affected by globalization, unless innovation is rapidly introduced and adopted. Is in this context that we envision the role for Chemical Engineering to be one of significant importance.

Until recently, the Chemical Engineering curriculum at the Universidad de los Andes, as well as, all the programs offered in other Universities in Colombia, could be described as traditional programs representative of a curriculum style followed internationally and particularly in the USA, almost invariably based on the concept of unit operations and transport phenomena with a process-based design capstone project, and all taught in a classical manner. Such style and content had remained in general unchanged since the 70s, as it is the case in many other countries around the globe. Many are the reasons for such state of stagnation. According to Wankat [5],

> "The stalled condition of reform results not from slow propagation of new research results but instead from a combination of the faculty's lack of basic pedagogical knowledge and the split in faculty interest between teaching and research. Other factors include faculty time constraints, university reward systems that favor research, lack of administrative support, and requirements to include more content in the curriculum"

On the other hand, Armstrong [6] emphasizes that we simply have not paid enough attention to the curriculum development in the last four decades.

Because, Chemical Engineering Education is strongly routed in fundamental sciences, chemical engineers have realized they can contribute significantly in many interdisciplinary areas. This trend has continued today as chemical engineers have become leaders in research areas such as materials, nanotechnology, tissue engineering, and convergent areas as bionanomedicine. This broadening of the discipline has led to calls by many different stakeholders to include more material in the curriculum as well as the development of additional skills. A key factor to consider is that employers are also demanding a greater level of competencies from engineers, versatility in a range of areas, not just the core technical domain.

Today, Chemical Engineering holds a rather unique position at the interface between molecular sciences and engineering, and this gives us many opportunities in a broad range of technologies where Chemical Engineering meets other science and engineering fields. The unique focus of chemical engineering on molecular transformations, processes, products, quantitative analysis, and multi-scale treatment of problems provides an ideal platform for productive interactions with a wide range of other science and engineering disciplines at boundaries that are among the most exciting technology areas of research today. A multi-scale approach should be understood in this context as the process of relating the chemical composition of a material to its properties, which are often determined on larger length and time scales than those pertaining to the atoms and molecules of which it is comprised. This broad applicability of chemical engineering fundamentals has become a defining feature of the discipline, and we are challenged to convey this vast domain to our students. Teaching students more about these particular areas of technology is exciting educationally, but it does tend to have a fragmenting effect on the discipline and represents a challenge for integration into the current curriculum [6].

In this contribution we provide a quick overview at how a Chemical Engineering Department in a developing nation is dealing with the insertion in their current curricula of multi-scale approaches to product and process design as well as the incorporation of innovation initiatives both for curricular reform and developing of skills for creative thinking and entrepreneurship in future Chemical Engineers, whose purpose is that of changing the local stereotype of Chemical Engineers as only problem solvers of well-defined technical problems for that of a professional increasingly skilled in understanding value creation and management of such generated value.

* Multi-scale approaches and Innovation in Chemical Engineering

As technological innovation plays an ever more critical role, Chemical Engineering practice has been challenged to shift from traditional problem solving and design skills toward more innovative solutions that seek to transform new knowledge generated by fundamental scientific discovery into the innovative new products, processes, and services required by society.

Currently, there are two frontiers of engineering, each of which has to do with multi-scales in time and space, and each of which is associated with increasing levels of complexity. One frontier has to do with smaller and smaller spatial scales and faster time scales, the world of so-called bio/nano/info, the convergence model recently put forward by MIT [7]. This frontier, which has to do with the melding of physical, life, and information sciences, offers vast, unexplored possibilities, and forces faculty and students to truly work across traditional disciplinary boundaries. The concept of convergence is not only an interesting approach to problem solving that interlaces disciplinary boundaries but a new paradigm in Science and Engineering. It integrates knowledge, tools, and ways of thinking from diverse fields to form an embracive framework for tackling complex problems that exist at the interfaces of multiple fields [8]. This frontier meets all the criteria of being inspirational and exciting for new generations of students. And out of this convergent world come products and processes that do not rest on a particular science or engineering field but on the integration of different approaches of such diverse disciplines, e.g., bionanomedicine.

The other frontier has to do with larger systems of great complexity and, generally, of significant importance to society. This is the world of energy, environment, food, water, manufacturing, product design and development, logistics, health care, and communications [9]. This frontier addresses some of the most demanding challenges due to their scope and complexity. Many of these challenges are the challenges that current and future engineering students have to face whether the skills for dealing with such difficult problems are imparted on them or not. Key drivers for change include social, economic, technical and geopolitical needs.

Among engineering disciplines, Chemical Engineering is a unique profession that couples understanding of molecular transformations, multi-scale analysis, and a systems view of problems. Chemical engineering today is a field dedicated to the engineering of molecular systems, applying principles from underlying sciences (e.g., chemistry, biology, materials science, and applied physics) and systems engineering (e.g., applied mathematics, operations research, and computer science) a truly multi-scale engineering discipline that fits perfectly to be a catalyst for convergence [6].

These requirements demand from chemical engineers, to follow a scientific approach that involves a multidisciplinary and multi-scale time and length integrated system approach to the complex simultaneous and, often, coupled transfer phenomena and nonlinear, non-equilibrium molecular processes that occur on different scales of length and time. That is, a solid understanding of how phenomena at a smaller length scale relates to properties and behavior at a longer length scale is necessary (from the molecular-scale to the production-scales). This has been defined as the triplet "Molecular transformations-Product-Process" integrated multi-scale approach of chemical engineering [10], which coupled with the convergence concept described above, promise to be the future of Chemical Engineering. How to change undergraduate engineering education, so that graduates approach these new paradigms, was the focus of the Frontiers in Chemical Engineering project conducted by the Council for Chemical Research (CCR) with NSF support, and one of the key challenges identified in a recent report by the National Research Council [8].

According with the conclusions of the Frontiers in Chemical Engineering project a new curriculum that is to incorporate Multi-scale aspects should [6]:

- Integrate all organizing principles and basic supportive sciences throughout the educational sequence and should move from simple to complex
- Be consistently infused with relevant and demonstrative laboratory experiences
- Provide opportunities for teaming experiences and use of communications skills (written, oral, graphic)
- Address different learning styles
- The curriculum should be consistently infused with relevant and demonstrative examples
    - Open-ended problems and case studies
    - Challenges of engineering practice: safety, economics, ethics, regulation, IP, market/social needs
- Include a first year chemical engineering experience

In addition, such a curriculum should be organized around some guiding principles, such as; molecular transformations, multi-scale analysis and system analysis and synthesis. Integration in time and across courses of the same level is also paramount. It is important to note here that the recent report by NRC on convergence identifies the organizing of curricula around common themes or guiding principles as one important aspect to foster the integration of disciplines [8].

Globally, there is a growing recognition that incremental innovation is not sufficient to deal with the grand challenges with which we are now faced. Innovation understood as "*the process by which new ideas are successfully exploited to create economic, social and environmental value*" [11] is yet to be fully engrained in current curriculums across Chemical Engineering Departments around the globe; although, important efforts are currently underway. More prominently, the CDIO syllabus (www.cdio.org) which envisions an education that stresses on fundamentals, set in the context of the product-system life cycle with components of **C**onception, **D**esign, **I**mplementation and **O**peration [12] and recently extended to include Leadership and Entrepreneurship, provides a very valuable resource for programs that seek to respond to stakeholder expressed needs in the areas of Engineering Innovation, Leadership and Entrepreneurship.

Led by pioneering programs such as those at MIT [13] and Stanford University [14], today a broad spectrum of colleges and universities throughout the USA have developed strong undergraduate engineering programs or courses that involve both innovation and entrepreneurship, including among many others, Rowan University [15], Rose-Hulman Institute of Technology [16], University of Maryland [17]. Smaller colleges and universities, such as Olin College [18] and Bucknell University [19], have also created innovative engineering entrepreneurship programs, showing that by fostering student interest in entrepreneurship and innovation early in the formation cycle, the knowledge gained significantly impacts direction towards more entrepreneurial and innovative careers [17].

* Our experience at UNIANDES

An overview of the organization of the current curriculum is shown in Figure 1, where Math, Sciences and the engineering principles form the foundation. Specialization, widening and integration are provided by means of electives courses. Design experiences are facilitated by three projects at the freshman (1st), sophomore-junior (2nd-3th) and senior (4th) years. The overall curriculum is focused on understanding Chemical Engineering fundamentals in an incremental order of complexity and in an increasingly complex context. It is believed that the sum of these components provides adequate curricular content to achieve the Student Outcomes and Program Objectives of the department.

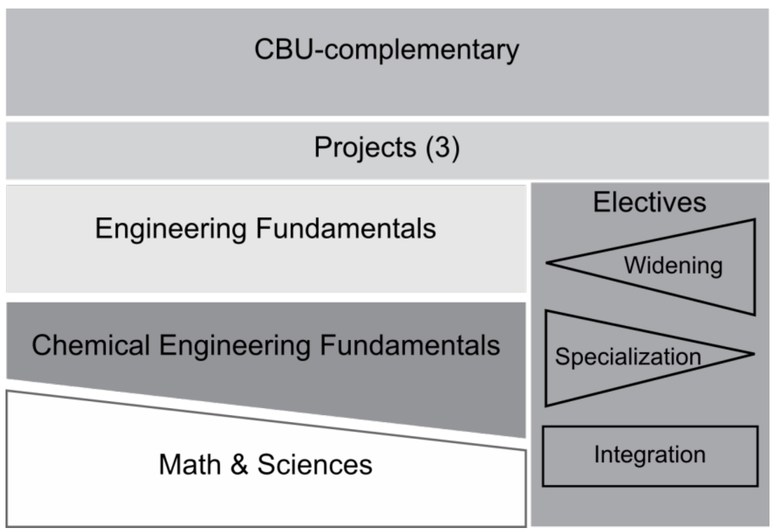

Figure 1 Chemical Engineering curricular components

As illustrated in Figure 1, the Chemical Engineering program curriculum at Universidad de los Andes can be split into the following components:

- General education courses (GEC): CBU and complementary courses.
- Math and science courses: Math, physics, chemistry and biology.
- Engineering fundamentals courses: General engineering courses.
- Chemical engineering fundamentals: Core chemical engineering courses.
- Elective courses: Electives aimed at broadening the specialization or integration of knowledge.
- Projects: Hands-on experiences in product and process design

General education courses: This component of the Chemical Engineering Curriculum is covered by a total of 24 credit hours; the CBU courses are based on the principle that every educated person should have at least a minimum academic contact with basic areas of knowledge such as the Arts and Humanities, Social Sciences as well as Science and Technology. The courses that make up the CBU are designed especially for students of all majors who begin their college education and provide educational elements other than those of basic and professional training of each specific program. The work and skills fostered by these courses involve reading, analysis and appreciation of primary sources, bibliographic referencing, and the consultation of resources. Critical discussion and thinking is encouraged during these courses and students write essays on these different topics.

Math and science courses: These courses provide students with a strong foundation in basic areas and provide the necessary background for the engineering courses to be taken later in the curriculum. These courses constitute the enabling subjects of any curriculum, in the layout by Armstrong [6] in his proposal for a new Chemical Engineering curriculum for the future

Engineering fundamentals courses: This curricular component provides both a strong foundation of scientific and technical knowledge, as well as tools and methods applicable in actual engineering practice. Currently, this component corresponds to 42% of the total credit hours for the degree.

Core chemical engineering courses: These courses provide the foundations of the core technical domain of chemical engineering and include traditional courses such as Fundamentals of Chemical Processes, Phase and Chemical Equilibrium, Chemical Reaction Engineering, Separation Processes, Transport phenomena, and Process Plant Design. It is important to note here that all core courses in the Chemical Engineering program incorporate laboratory experiences as part of the regular classes in line with the new curriculum proposal by Armstrong [6].

Electives: The chemical engineering curriculum includes 24 credit hours of electives. The majority of electives taken by our students are Engineering Topics or Basic Math and Science courses. Flexibility in this portion of the curriculum allows students to explore choices in education and tailor their curriculum based on interests and strengths. These electives also provide the opportunity for students to freely pursue double majors.

Projects: In the engineering curriculum at Uniandes there is a chain of three projects, each with a particular emphasis, which seeks to strengthen competencies such as, teamwork, problem solving, interaction with the environment, creative thinking and entrepreneurship and life-long learning among others. The initial project conducted during the freshman year provides the first hands-on experience with Chemical Engineering for first year students in the program. The expectation of this first project, for the student, is to solve a well-defined problem as an engineer does in the context of any profession. This design experience also aims to develop teamwork skills, interdisciplinary collaboration, and project-based learning using a guided inquiry led by the structor.

The second design experience, conducted during the transition from sophomore to junior years, is what we call the mid-program project. The work to be developed in this project aims to provide students with adequate space for carrying out the integration of knowledge, skills and attitudes necessary to adequately perform a task, action or thought process characteristic of the professional practice in a more defined context. This design experience also aims to develop skills of teamwork, interdisciplinary collaboration, driven by a project-based learning scheme using a guided inquiry. This project is currently focused as a hands-on experience in product design and also represents the first experience at applying a multi-scale approach to design and application of innovation practices based on an "inside the box" approach. The inside the box method, a Systematic Inventive Thinking Approach [20], is based on the idea that better and quicker innovation can take place when an individual works closer to his or her familiar world using well established and identified rules. Such a method works well for novice students who are still in the process of learning how to generate ideas for product design, since it is a strategy that allows students to ensure that their innovation ideas are quickly followed by implementation using resources close at hand.

The final project in this design experience is the Graduation Project (a compulsory requirement for graduation), conducted during the senior year, with emphasis in research or applications. The independent work to be developed in this project aims to provide students with a space for carrying out the integration of knowledge and skills necessary to properly perform a very specific task which involves components of either Product and/or Process Design. Depending on the level of complexity, such project can be conducted by one or two students.

Comparing the curriculum structure in Fig. 1 with that proposed by the Frontiers in Chemical Engineering project [6] and benchmarking against the CDIO syllabus [12], we come to the conclusion that our current structure already incorporates some of the desirable attributes for a novel curriculum in Chemical Engineering. What is missing in this structure are the most recent proposals for undergraduate curriculum reform; meaning the incorporation of multi-scale approximations to design and the innovation, leadership and entrepreneurship components.

As a result of our recent ABET accreditation process and in line with our commitment to continuous improvement; input from different sources has given us the drivers for further revision of our current curriculum as illustrated in Fig. 1. Note that prior to considering an intervention of the curriculum, a number of important issues had already been addressed in some detail due to our upcoming reaccreditation process to star in 2016. Those issues include:

- Mapping of students outcomes and program objectives
- Mechanisms and tools for monitoring and quantifying the attainment of those graduate attributes.
- Organization of the curriculum according with the components in Fig.1 and distribution of student outcomes to be fostered by each course in the program.
- Establishing an evaluation process whereby each individual course could be reviewed for its content, teaching/learning approach and assessment procedures.

Key questions that we have pondered about are centered on what defines a chemical engineer in this century, what are the current trends and how best to equip our graduates with competitive skills both in the context of our country and internationally. Taking and innovator´s approach to our curricular intervention, we have tried to solve four simple questions [21]:

What orthodoxies can we challenge?

How can we best harness the current trends in the field, both in research and education?
How can we take advantage of our available resources and strengths?
What are the most important needs in our country and how can we provide solutions through our graduates?

The information gathered in the process of answering the previous questions provided us with the elements that captured well the consensus within the task force group set by the Department for this purpose. These include:

- Chemical engineering in Colombia needs to move from a purely process-based program to a balance mix between product and process design.

- The so-called enabling sciences: Biology, Mathematics, Chemistry and Physics are already well engrained in our current curriculum.

- A new set of organizing engineering principles needs to be established. The approach based on molecular transformations, multi-scale analysis, system analysis and synthesis as proposed by Armstrong [6] was identified as a very good starting point.

- Innovation and Entrepreneurship was identified as significant element missing in the implemented structure. This component is currently one of strategic importance in our country and one that addresses very important needs from different stakeholders.

- Enabling technologies are available in our institution that will allow for novel and interesting implementations. These tools included computing infrastructure, state of the art labs, software availability, and professional engineering skills of our faculty.

Coupled with the fundamental technical drivers for curriculum reform identified above are also the possibilities for improvements in both mechanisms for delivering educational content through the web as well as methods for more effective in-class or blended education which currently our University is in the process of implementing.

Given our existing capabilities both in faculty and infrastructure, the main educational and technical drivers chosen for implementation were:

- Process/product design as a unifying principle for integration into hands-on experiences currently implemented
- Multi-scale analysis as organizing principle for core Chemical Engineering Courses
- Basic Innovation and Entrepreneurship content in specific courses

In what follows we illustrate the implementation in selected courses within the Chemical Engineering Curriculum at UNIANDES, one at the undergraduate level, one at the graduate level. Table 1, summarizes the most significant aspects of the implementations.

Table1. Implementing a multi-scale approach to product and process design in specific courses

Dimension/Level	Undergraduate: Mid-Career Project	Graduate: Advanced Transport Phenomena
What has been implemented	Process/product/properties design as a unifying principle	Multi-scale analysis as organizing principle
What is taught	Implementation of simple multi-scale principles for Product Design Impact of molecular-events on macro-scale phenomena Strategies for designing disruptive products Innovation activities driven by an “inside the box” approach.	Principles of multi-scale transport phenomena • Continuum: Integrated approach to continuum momentum, heat and mass transport for chemically reactive and none reactive systems at micro/meso/macro-scales. • Discrete: Momentum, heat and mass transport for chemically reactive and none reactive systems based on inter-molecular and inter-particle interactions. • Coarse graining: Strategies for combining continuous and discrete approaches in the solution of complex multi-scale problems.
What is brought in	Simple conservation laws Physical property estimation Molecular interactions Quantitative structure-property correlations, different types of molecules, mixture properties.	Fundamentals of transport phenomena and conservation laws. Heterogeneous systems and interfacial phenomena. Understanding of modeling and simulation
Crosscutting Concepts	Structure and function Conservation laws Scaling System and system models Stability and change Disruptive technologies	Conservation laws Heterogeneity of structure, properties and function Manipulation of the atomic/molecular level to influence macroscopic properties Novel and potentially disruptive product and processes

Types of problems	Open ended problems • Particles or emulsions for active agents delivery • Drag reduction • Viscosity reduction. • New products for cosmetic, food and personal care. • Polymer development.	• Discrete: Prediction of properties from intermolecular and or inter-particle potentials using computational tools (e.g., GROMACS, LAMMPS, HOOMD). Aggregation and assembly • Continuum: Complex fluids and flows both with and without reaction • Coarse graining: Particle-molecule interactions, interparticles interactions under complex flow conditions.
Lab. Experiences	Making the products and/or prototypes	▪ Estimation of viscosity and diffusion by Brownian motion experiments with computational replication using GROMACS, LAMMPS. ▪ Flow or heat transfer visualization experiments and computational replication using CFD ▪ Coupled momentum, heat and/or mass transport experiments with replication using multi-scale computational approaches.

Mid-Program Project: application of the triplet Properties-Process-Product

Students taking the mid-term project class are for the most part year 2 chemical engineering students that have only basic knowledge and skills with respect to the practical application of math, sciences and fundamentals of chemical engineering. Subjects such as transport phenomena, and reaction engineering that form the basis of chemical product design are undertaken in the third year of their studies. Due to this lack of fundamental chemical engineering knowledge, their introduction to product design and innovation has to be focused on well-defined problems, whereby the students start with a generic requirement for a product or process and trough ideation approaches, such as those, provided by the inside the box method they narrow down the ideas to be implemented.

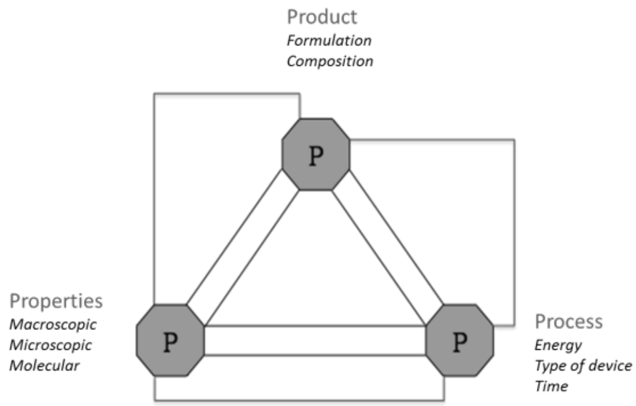

Figure 2 Schematic that illustrates the interrelations between the triplet product/process/properties

At the product level the systems composition (formulation) is considered, at the process level the type of devices used (e.g., type of mixer), time for processing and energy consumption while at the property level, a multi-scale approach is used where the macroscopic response is gaged by means of macroscopic tools such as rheology and at the microscopic level particle size distribution of the phases is one of the possible variables to follow.

Figure 2 known as the 3Ps tool, is used in the context of this course as the main tool to guide the design of a formulated product. The implemented methodology is as follows:

- Needs identification.
- Generation of ideas to meet the established needs. At this point, the “inside the box” approach to innovation is used to generate those ideas.
- Selection of the most promising concepts and translation of such concepts into product properties. Here, the 3P tool (see Fig.2) is used as driving element for product design.
- Process design for the production of product or prototype at lab scale.
- Hands-on experience for implementing product or prototype

Assessment of impact and motivation:

As part of our continuous improvement process, this course is assessed every semester in order to determine what changes needed to be made. In addition, assessment is performed in order to determine whether the course is meeting intended programmatic goals. To meet the outcomes of the course, students are required to submit evidence relating to their achievements. This can take the form of reports, oral presentations, drawings, posters, computer programs or scripts, and other related material.

Recent surveys (first and second semester of 2014) of student cohorts have shown that our new approach enhances student motivation, their focus on self-directed learning, while allowing flexible learning and teamwork. There has also been a significant increase in student engagement with the broader and independent learning process. Despite of being a more challenging class due to the open-ended nature of the projects, the percentage of students that expresses their satisfaction has been above 90% for the two semesters of 2014 according to student's surveys.

A sample statement collected from a student survey is the following:

"I found it a very good opportunity to do projects and applications on different topics of the program. I would find it interesting that in this area the students could interact and do projects with students from other engineering programs in order to develop new ideas and have a multidisciplinary team work. I enjoyed the class!"

Multi-scale Transport Phenomena

As it stands today Chemical Engineering is focused on properties of condensed matter systems on length scales that span roughly 10-12 orders of magnitude, ranging from 10 Å as in catalytic processes to a few hundred meters for large processing plants. The reason why there is no single, all comprising model for describing transport phenomena on all scales, relevant to Chemical Engineering or any other science for that matter is that nature exhibits complex hierarchies, which occur in chemistry and engineering devices as well as in biological systems. It should be clear that at the angstrom-scale there are only atoms but then on larger scales these basic building blocks ensemble into complex hierarchical structures, which are treated with different approximations based on the level of coarse-graining introduced. Figure 3, illustrates our schematic approach to Transport phenomena as organizing principle.

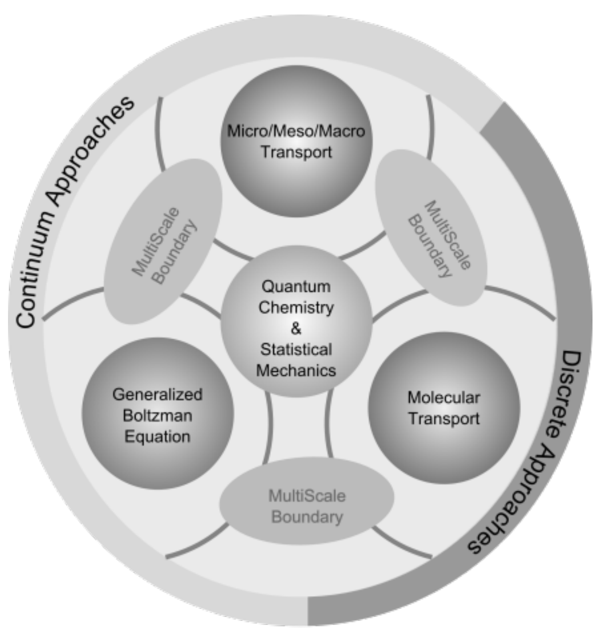

Figure 3 Schematic of a multi-scale approach to transport phenomena

The implemented course is basically an introduction to the foundations of multi–scale transport phenomena presented in a unified manner. The mathematical and physical science level of sophistication are at the upper undergraduate level, and first year graduate level; students who have been exposed to vector calculus, differential equations, and calculus-based physics are believed to be adequately prepared to handle the material presented.

The basic foundations of both transport phenomena (and thermodynamics for that matter) lie in the descriptions and treatment of large collections of interacting molecules and atoms. From this perspective, treating transport problems at different scales of length and time is a matter of properly identifying the right scales for any particular system. Based on this somewhat simplified view, the course has been divided into four major modules, as follows:

Molecular perspective: At the molecular level we are interested in the fundamental mechanisms of momentum, angular momentum, energy and mass transport, as determined from molecular structure and intermolecular forces. This is a field commonly associated with physics and physical-chemistry; however, it is becoming more common for chemical engineers to get involved at this level. Particularly, if the processes involve complex molecules, such as proteins, enzymes, or polymers; extreme conditions of pressure and/or temperature; chemically reacting systems; ionic systems; or very small scales of time and space, such as those encountered in microfluidics and nanotechnology. In this module, students are exposed to simulations tools such as LAMMPS [22], GROMACS [23] and HOOMD [24] which are used as part of an assigned project that involves both experimental and computational components (see Table 1) designed to get the students to utilize the different approaches and tools introduced in the module. The project is developed and coordinated by the instructor and undertaken by the students in teams of 3-4 students.

Microscopic perspective: The microscopic approach is exemplified in the landmark textbook [25]. This approach calls for an a priori knowledge of the phenomenological coefficients (i.e., thermal diffusivity, mass diffusivity, momentum diffusivity) in order to solve the partial differential equations that describe the conservation laws. The reader should recognized that one possible approach to the description of a fluid in motion for example, is to examine what occurs at the microscopic level where the random motions of individual molecules can be followed in time, the molecular perspective of the previous module. However, the resulting many-body problems of molecular dynamics is quiet complex under normal circumstances because the systems of interest usually contain an enormous number of molecules. At this macroscopic level of observation, the description of fluid motion may call for an average of the forces of interaction between the fluid and the bounding surface, but not the knowledge of the instantaneous forces of interaction between the surface and individual molecules of the fluid. For this specific module, students use well established commercial software such as COMSOL Multiphysics® or ANSYS®, as part of an assigned project that involves both experimental and computational components (see Table 1). The project is developed and coordinated by the instructor and undertaken by the students in teams of 3-4 students.

Mesoscopic perspective: To get the macroscopic balances, it is necessary to integrate the equations of change over the entire volume of a flow system. There are, however, situations in which we need to integrate over all the variables, except for one or two, and then solve the resulting differential equation. In the mesoscopic description to transport phenomena, particularly those that take place in heterogeneous media, the diffusion process in the medium is analyzed using an up-scaling method, in which the local phenomena at the microscopic level are described at the macroscopic scale by means of effective dispersion tensors. Both theoretical and computational tools are used as part of content delivery. This module is assessed by means of oral presentations by students in teams of 3-4 students.

Multiscale perspective: The foundation of multiscale modeling as applied to transport phenomena problems is based on Quantum Mechanics (QM). Quantum mechanics calculations provide the essential parameters such as bond lengths, bond angles, dihedral angles, and force field potentials essential for describing the interactions between atoms, molecules and particles. Developing interatomic potentials based on conformations sampling and energies calculated using QM provides an accurate and sophisticated method for performing molecular simulations, which provide accurate material properties. However such an approach is a very expensive one from a computational perspective. Therefore, coarse graining is introduced as a method to simplify the structure of complex molecules for example [26]. This module focuses on different approaches to perform coarse graining and introduces different modeling techniques that can be used to solve simple problems that require a multiscale approach for their solution. This module is assessed by means of and individual project, selected in agreement with the student´s advisor or research tutor and that complies with the expected outcomes of the course.

The students are given freedom in specifying the project deliverables and also the methods whereby they achieve the learning objectives. This is deliberate as the instructor gives only technical guidance and course lectures are for the most part generic and not specific to the wide range of projects that the students might choose. Therefore, successful completion of the course requires students to design and undertake their own physical or computational experiments and thus take charge of their own learning.

The following are some reflections on recent cohorts from the instructor's point of view:

- At the end of the semester, there is a high degree of enthusiasm exhibited by the students taking the course. Although some students complained in the surveys of the large workload, there are almost no drop-offs for the course, most students seem highly involved in their project(s) particularly the final one that involves multiscale approaches. Sample statements collected from a student survey are as follows:

  "It is a very interesting course, projects and work proposed in this class expand the knowledge on transport phenomena"

  "Understanding the issues and their development has been facilitated by both teacher and classmates ... the study environment is excellent and the tools available are very good"

- The final reports on individual projects are for the most part of a high quality suggesting both: student interest and achievement of learning objectives.
- During the three years that this course has been offered, evidence has been seen of students taking charge of their own learning as they successfully take control of their projects, their time management and the design of their own physical and computational experiments.

- The level of participation and input into lectures and oral presentations by their peers and almost 100% attendance suggest that students develop a legitimate interest in the course throughout the semester.
- Written feedback on the student surveys showed that to a high degree the students liked the way the subject was presented but that they had indeed put in more hours than for any other subject.

Conclusions and perspectives

The Department of Chemical Engineering at Universidad de los Andes has begun the process of incorporating an integrated framework for a multi-scale approach to product and process design in the curriculum, in the first exercise of its kind for any program in Colombia. The first stage of implementation into our curriculum was introduced in 2013 with the selection of two specific courses for redesign, one at the undergraduate level (e.g., Mid-Program Project) and other at the graduate level (e.g., Advanced Transport Phenomena), this process will continue in stages in the upcoming years with the redesign of our core Chemical Engineering Courses.

The organizing and unifying principles for integration revolve around three specific drivers: i) Process/product design as a unifying principle which has been integrated into mid-program project; one of our hands-on experiences for undergrads. ii) Multi-scale analysis as organizing principle which was incorporated in the design of our current advanced transport phenomena course, a graduate level class, open to advanced undergraduate students. iii) Basic innovation and entrepreneurship content which is currently been incorporated in the context of our mid-program project.

Many issues that have been already identified with a traditional curriculum [6, 27, 5], as well as, our own process of continuous improvement, have motivated this intervention. There are challenging issues to resolve, in particular related with the development of teaching material and textbooks and core courses redesign, but many positive features have emerged so far. The positive reviews of what has been implemented so far by renowned members of the Chemical Engineering community, both in Colombia and overseas, as well as positive comments from students, have given us the impetus to continue with this challenging quest.

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