## Executive Summary

When asked to explain the substance of chemical engineering, we might naturally describe the knowledge base as organized into, e.g., thermodynamics, transport phenomena, reaction engineering, and so forth. Indeed, these headings are found in textbook titles and university course descriptions, they are usefully related to the foundational sciences, and they draw diverse phenomena and operations under an economical number of physical principles.

Even so, they are habit; and the same knowledge base might be fruitfully arranged in other ways. Thus, participants in the New Frontiers in Chemical Engineering Education Workshop I were asked to describe the foundational blocks for an undergraduate chemical engineering curriculum, specifically avoiding the terms “material and energy balances”, “thermodynamics”, “transport phenomena”, and “reaction engineering”.

Work was done in five groups. Reports from individual groups are recorded in the Proceedings; they are summarized here. To varying degrees, the groups addressed:

- **subject matter of the profession** - explicating the facts and the operations, the things that chemical engineers know about and know how to do, the knowledge and the skills.
- **attributes of the graduate** - more than knowing and exercising the subject matter, the graduate should have certain attitudes, capabilities, habits, approaches to problems. Such things are the characteristics that might make an instructor say of a student, “now that one thinks like an engineer!”
- **ways to organize the subject matter** - building blocks that express and convey what chemical engineers know and do. The same set of blocks might be assembled in different ways to form a curriculum, that is, the sequence of experiences offered to students.

Group 1 arranged the blocks in a hierarchy that ran from foundation sciences to engineering design. Thus they began with a subject matter foundation (mathematics, physics, chemistry, biology) but transformed to engineering operations (modeling, design) by the end. There is an implied structure of prerequisites in this curriculum - engineering synthesis resting on scientific principles - but no suggestion that one finishes a topic and need not revisit it in later courses.

Group 2 stated attributes desired in the graduate. They then described alternative types of curriculum, including a case study approach (in which the cases range over a variety of ChE areas of application), a science paradigm (in which the foundation sciences inform the curriculum over all four years via “integration tools”), and a turnkey approach (which focuses more on the use of tools than the development of tools). Their building blocks included electives and cultural enrichment as a part of the engineer’s experience.

Group 3 defined the subject matter largely along traditional lines. They included items of professional practice, such as ethics and team skills, in addition to the technical topics. They then arranged the curriculum according to physical length scale, so that students would first encounter electron-shell phenomena, proceed to molecular phenomena, and finally to macroscopic scales. In each level of organization, they drew from the knowledge base, thus covering the traditional topics in the new context. Furthermore, at each level they distinguished analysis and synthesis activities, thus introducing design early into the curriculum.

Group 4 also identified core chemical engineering subject matter, and suggested that the mathematics/physics/chemistry/biology foundation could be more integrated throughout the ChE core, instead of being front-loaded. They identified molecular description and transformation as key features of chemical engineering science, and they pointed to the importance of integration and synthesis. They also identified personal and professional skills to be cultivated in the graduate.

Group 5 proposed a list of building blocks that included particular sciences, the useful generalizations of equilibrium and rate processes, experience in laboratory, and development of professional skills. They then conceived of a vertical integration scheme. That is, after identifying the building blocks with course subjects, they would undertake to reinforce each block in each year of the curriculum. Further curriculum design would arrange the level of difficulty appropriately. In addition, the group supplied several ideas on presentation methods.

Motivated by the science foundation articulated by all groups, the science integration of Groups 2 and 4, the length-scale organizing pattern of Group 3, the molecular emphasis of Group 4, the higher-level engineering tools of Groups 1 and 2, and the importance of synthesis from Groups 3, 4, and 5, we derive four organizing principles for a chemical engineering curriculum:

- **molecular processes** - fundamental processes at the atomic and molecular level. All groups reaffirmed the foundation of physics, chemistry, and biology on which chemical engineering rests. In this category, we might include physical and chemical bonding, chemical and biological reaction mechanisms and pathways, and the contrast between bulk phase and interface processes. Notions from kinetic theory, quantum mechanics, and the comparison of rate and equilibrium processes might also play a part.
- **analysis** - from differential equations and continuum mechanics to statistics and laboratory data, all groups reaffirmed the use we make of mathematics. In this category we address the conservation laws, the variation of state variables in time and space, the fruitful analogies in diffusion and convection. Rate and equilibrium again play an important part.
- **multiple scales** - chemical engineers treat semiconductor electron orbitals, biological cells, packed towers, and atmospheric dispersion. Understanding the similarities and differences in the way analytical tools are applied at different length scales - the approximations and assumptions appropriate at each level - reinforces the versatility of the tools and the general notion of problem-solving. Finally, the scales are bridged: molecular simulations connect molecular properties to macroscopic behavior, and rate expressions for catalysis influence the reactor cooling requirement.
- **synthesis** - design, creation, extrapolation, building, scale-up, envisioning and specifying a new product, assembling systems from component systems, understanding how complex systems vary in time, how humans and equipment interact in control rooms and plants, how humans and equipment are organized to form businesses that operate processes, abide by regulations, conduct R&D, and market products.

Each of these principles offers adequate scope for laboratory experience, computational skills, techniques of problem-solving, and application examples. However, an emphasis on design, economics, ethics, safety, and other professional skills might fall most naturally under the synthesis principle. Hence the suggestion from Groups 2, 3, and 5 that all blocks be addressed within each year would help to ensure that these important areas are not neglected.

These conclusions, and the work on which they are based, will form the basis for further development of the curriculum in Workshop II. We welcome comments and suggestions from the chemical engineering community.