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Teaching Transport Phenomena in Biological Systems*

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Teaching transport process to students in medical and biological engineering is very important for their understanding of many of the fluid flow, heat transfer, and mass transfer processes related to biological systems. The classical approach to transport process presentation is compared to an analogical systems approach that is more conceptual and less mathematical. Advantages of the latter approach are that students can more quickly grasp the meanings of processes, and that a broader range of applications can be accommodated.

INTRODUCTION

TRANSPORT PHENOMENA are especially important in medical and biological systems, and should be considered a fundamental subject for biomedical engineering education. The classical transport phenomena are considered to be heat conduction and diffusion mass transfer with the occasional addition of momentum transfer (also identified as fluid flow).

Examples of these processes abound. Inside the human body, for instance, fluid flow, heat transfer, and mass transfer can be seen in capillary blood flow, cutaneous heat loss, and kidney filtration. In medicine, these same three processes can be seen while pumping reagents throughout blood analyzers, adding heat to neonates, and constructing bioartificial organs. In non-medical examples, these three can be found in sewage flow in pipes, ventilation systems for buildings, and reverse osmosis desalinization. Whether the motivation is analysis to understand physical phenomena inside the body, design of equipment to improve medical care, or design of systems to improve public health, produce nutritious food, or protect the environment, there is no more important subject matter to understand than transport processes.

Indeed, in the *Biomedical Engineering Handbook*, Bronzino [1] attempts a definition of biomedical engineering, giving a list of biomedical engineering pursuits. Nearly all of these involve transport phenomena in one form or another. A further look at the contents of the handbook reveals chapters on the cardiovascular system, electrophysiology, biomaterials, biosensors, tissue engineering, artificial organs, and physiological modeling, just to name a few. Transport phenomena form the basis for the proper operations of each of these topics.

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CLASSICAL METHODS

There is a great deal of similarity among the transport process. This similarity may be shown in any number of ways, but the way that became popular was to present a mathematical analysis of heat conduction and diffusion mass transfer in generic form [2]. Fluid flow, also called momentum transport, was often left out of this analysis because fluids behave somewhat differently from heat and molecular mass. Additionally, convective heat and mass transport requires a different mathematical approach.

Once the general mathematical equations had been shown, many specific examples were presented to illustrate the general application of these equations. However, each application usually involved enough special conditions that the generalities introduced by the basic equations were often lost in the details of the problems.

Chemical engineers retained the mathematical approach, but added unit operations [3]. Faced with the analysis and design of equipment with many functions in common, they visualized the problems as consisting of a series of black boxes each with certain essential characteristics. There were black boxes for pumps, heat exchangers, and membrane separators, to name a few, and each of these was identified by generic input and output characteristics. A total system to manipulate some chemical process could then be built from an assemblage of unit operations modules. For instance, a distillation process would probably include pumps, pipes, heaters, heat exchangers, and cooling modules. The chemical engineer, having studied properties of each of these modules, would be familiar with the overall operation of the system as the sum of its parts. When some chemical engineers began to be involved in biotechnology, they used the same approach to model bioreactors, except that now they had to treat living cells as another type of unit operation [4].

Thus, they characterized microbial responses into lag, growth, stationary, and death phases, and tried to maintain bioreactor conditions constant enough that the cells in the bioreactor didn't change form, as living organisms sometimes do, and display a different range of characteristics.

This unit operations approach to the study of transport processes became extremely successful because it added an element of engineering analysis and design that was different from an applied mathematical approach. Instead of the ideal conditions required in the mathematical approach, a series of measured physical parameters was introduced to account for non-ideality. However, much of early biomedical engineering was spawned from electrical engineering, and these biomedical engineers were not exposed to transport processes in their educations because the unit operations approach was considerably different from the systems approach used in other courses.

As long as education of medical and biological engineers took place in traditional engineering departments, the types of courses and approaches used in these courses were dictated by classical methods in the specific field. Thus, biomedical engineers coming from electrical engineering, who were often mainly interested in bioinstrumentation, imaging, and electrophysiology, did not take transport processes courses: they took network theory and systems courses instead. Biomedical engineers coming from mechanical engineering, who were often mainly interested in biomechanics, bioheat transfer, and blood flow, did take transport processes (with a mathematical approach) but often did not take network theory. Biomedical engineers coming from chemical engineering, concerned mainly with heat transfer, separation processes (as in the artificial kidney), and, later, biotechnology, took transport processes with a unit operations flavor. Thus, the subject of transport processes was taken largely by biomedical engineers with chemical and mechanical engineering roots. Many of the important transport processes books were written by those coming from chemical engineering [2, 5–6]. While not a fundamental transport processes text, *Bioprocess Engineering* by Shuler and Kargi [4] continued this tradition while reflecting the trend toward cellular and subcellular biotechnology.

THE ANALOGICAL SYSTEMS APPROACH

Schneck [7] was one of the first to recognize that transport process techniques could be applied to some unorthodox variables such as information flow. With a little more thought, it becomes clear that, with the correct approach, transport process can include not only the traditional fluid flow, heat transfer, and mass transfer, but also electricity, mechanics, informatics, psychology, population dispersion, and others. In each of these cases, there is a motivational force, a substance that flows from one state or location to another, some reservoir containing the substance, and a resistance to flow that limits that rate at which the substance moves. Because the concepts of transport processes can be so radically extended, it becomes imperative that medical and biological engineers of all persuasions become familiar with transport processes. To make transport processes a universal requirement, however, requires that the educational approach move beyond the chemical engineering unit operations basis.

The analogical systems approach is one means to do this. This approach borrows some of the systems concepts from electrical and mechanical engineering, and emphasizes similarities among systems as taught in chemical and agricultural engineering. The analogical systems approach requires that students become familiar with sources and sinks, resistance, capacity, and inertia. Effort variables are those that cause an action to occur; flow variables are those things that actually move. Resistance, capacity, and inertia relate flow and effort variables in predictable ways. Resistance, for

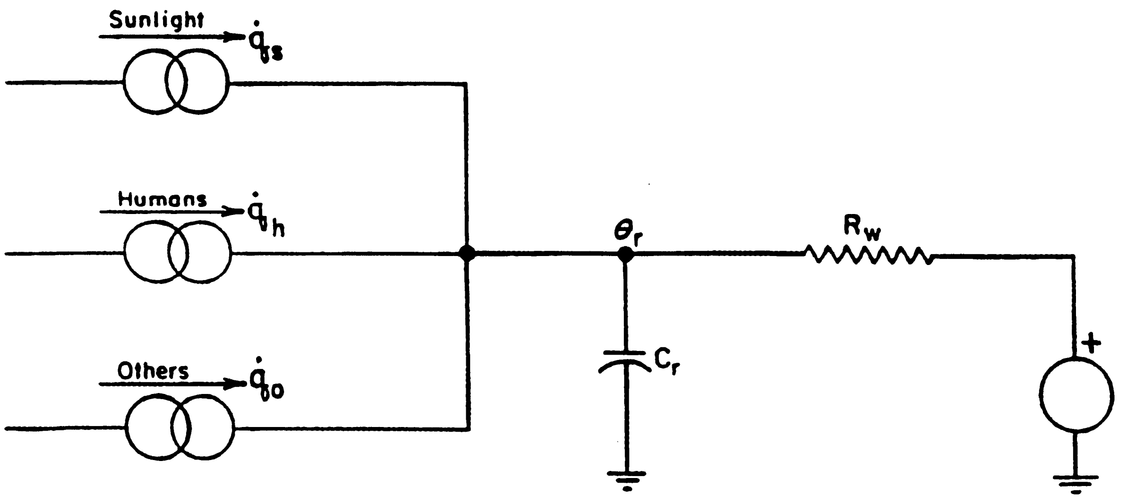


Fig. 1. Systems diagram representing a heat balance in a room with human occupants, sunlight, and other sources [8].

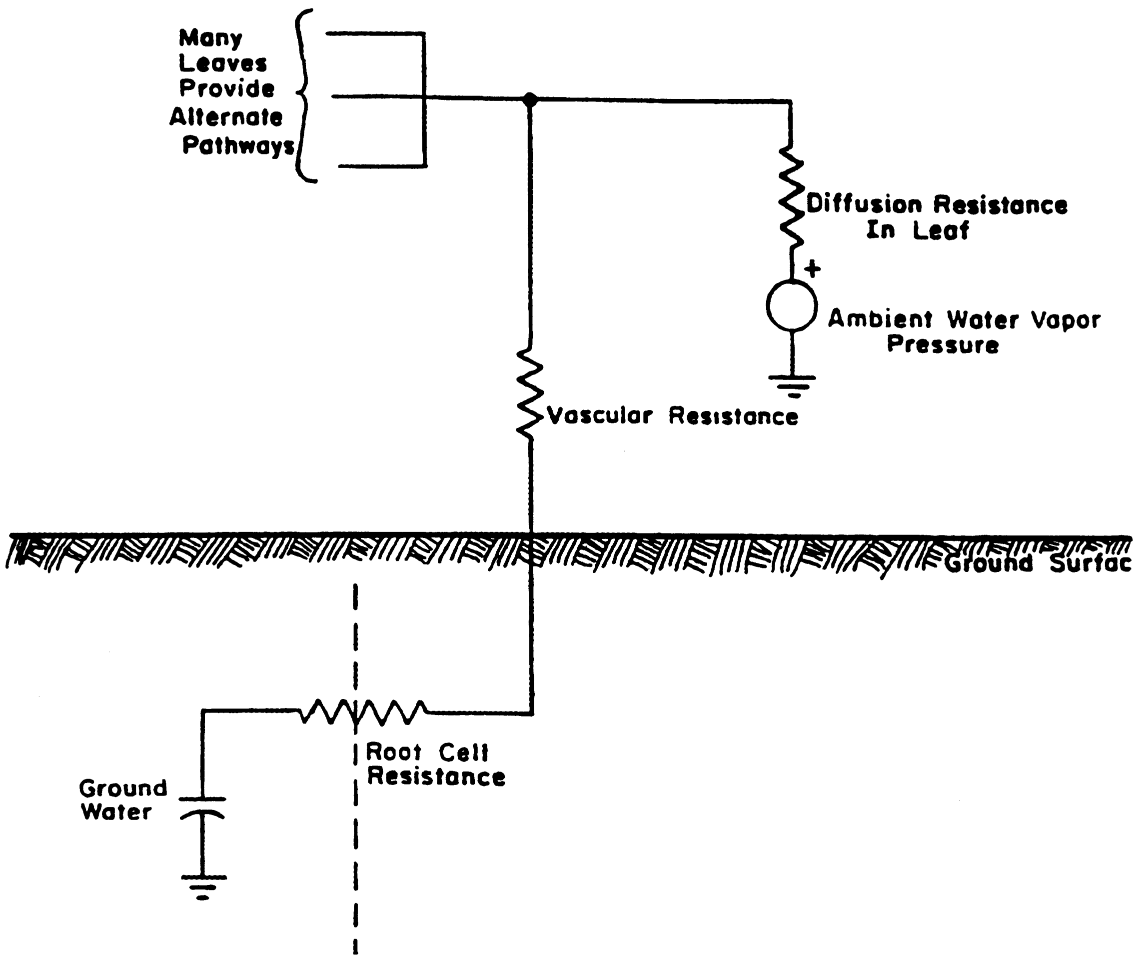


Fig. 2. Steady-state diagram of water flow in plant [8].

example, is the ratio of the effort variable to the flow variable.

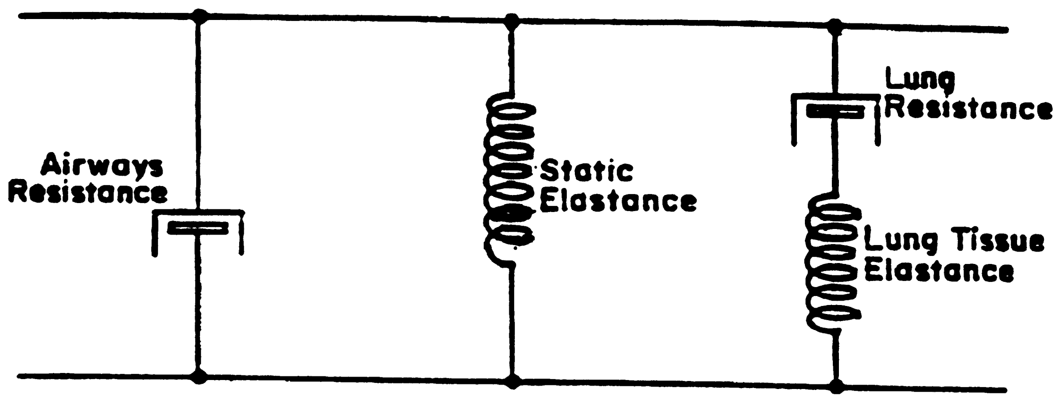
Once the properties of these elements are known, the solution to any transport process problem can be sketched out in conceptual form. Quantitative details can then be added later to solve the problem.

Systems diagrams of transport problems are easily sketched as electrical analogs (Figs 1 and 2), although there are alternative representations possible (Figs 3 and 4). There is a functional equivalence between elements of the physical system and the analog, as shown in Fig. 4, to aid in spatial understanding of the system. Similar diagrams have appeared in other texts [6], but there they were not a central aspect of transport process understanding as they are in Johnson [8].

There are several strong advantages to the analogical systems approach that are particularly apparent when considering the broader applications of medical and biological engineering. Not only is the analogical systems approach able to represent the similarities among the various traditional and nontraditional transport processes, but it also represents the similarities among different biological scales, from subcellular to ecological. Thus, there is a parsimony to the analogical systems approach that economizes on the size of the essential knowledge base that medical and biological engineers must possess.

Another advantage of this approach is that it de-emphasizes the mathematical basis for transport processes and substitutes more concrete concepts. Thus, as a means to introduce students to transport processes, it can seem more real and understandable. There are biomedical engineering students who are very comfortable with mathematics and can quickly grasp the subtleties of differential equations, boundary conditions, and closed-form solutions. However, there are also biomedical engineering students who must be shown something more than an equation in order to generate understanding [9].

Creativity, innovation, and flexibility are considered an engineer's greatest assets, but these are largely right-brain functions. Left-brain dominant individuals think by forming textual or logical concepts and are particularly good at mathematics. Schooling often discriminates against right-brain functions in favor of left-brain functions [10]. The analogical systems approach can help to foster right-brain thinking as well as give a concrete understanding of potential applications.



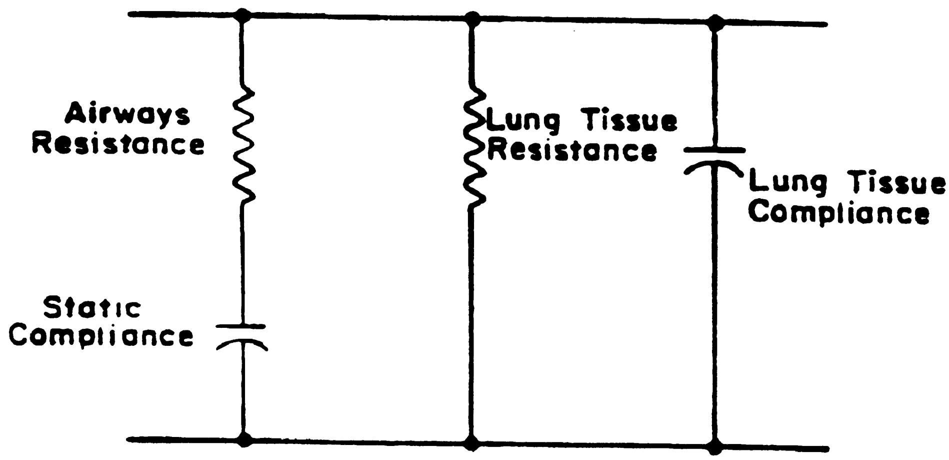


Fig. 3. Two representations of the pulmonary impedances for dogs. The top representation is the mechanical analog proposed by Bates et al. [11], the bottom representation is the corresponding electrical diagram. Although the two are analogs of each other, they appear to have different connections as well as basic elements. The difference is due to the different meanings of connections [8].

EXAMPLE

Consider the respiratory system analog in Fig. 3. The classical mathematical approach to the description of air flow in the respiratory system would probably begin with a pressure balance on the system [12]. Some mathematical description of airways geometry would be used, which often assumes the form of the Weibel model [13]. Airway mechanical properties would also be included. Finally equations would be developed to describe the flow rates at various points in the system. These would then be solved in either exact or numerical forms, and, probably, graphs would be developed to illustrate flows in various parts of the respiratory system. The written description of this analysis would feature many equations separated by written descriptions of necessary operations.

If the unit operations approach were to be applied to respiratory flow, it would be based on a large amount of empirical data. The respiratory system would first be disassembled into a series of compartments such as the airways, lung tissue, and chest wall. Pressure/flow relationships in tabular, graphical, or mathematical form would be given for each of these compartments, and the functioning of the entire respiratory system would be inferred from the assemblage of pressure/flow relationships for each of the compartments.

The analogical systems approach would first produce a conceptual diagram as in Fig. 3 (bottom). Essential characteristics of the respiratory system would be contained within the symbols used in the diagram. For instance, resistances are known to dissipate energy, and capacity elements (known as respiratory compliance) store flow and act as springs. When both are present, there is a negative phase difference between applied pressure and resulting flow.

None of these three approaches is sufficient in itself. Starting with the analogical systems approach allows the overall concept of the system to be quickly and easily sketched. This adds context in which to develop details. Drawing upon the empirical nature of the unit operations approach, descriptions of respiratory resistances

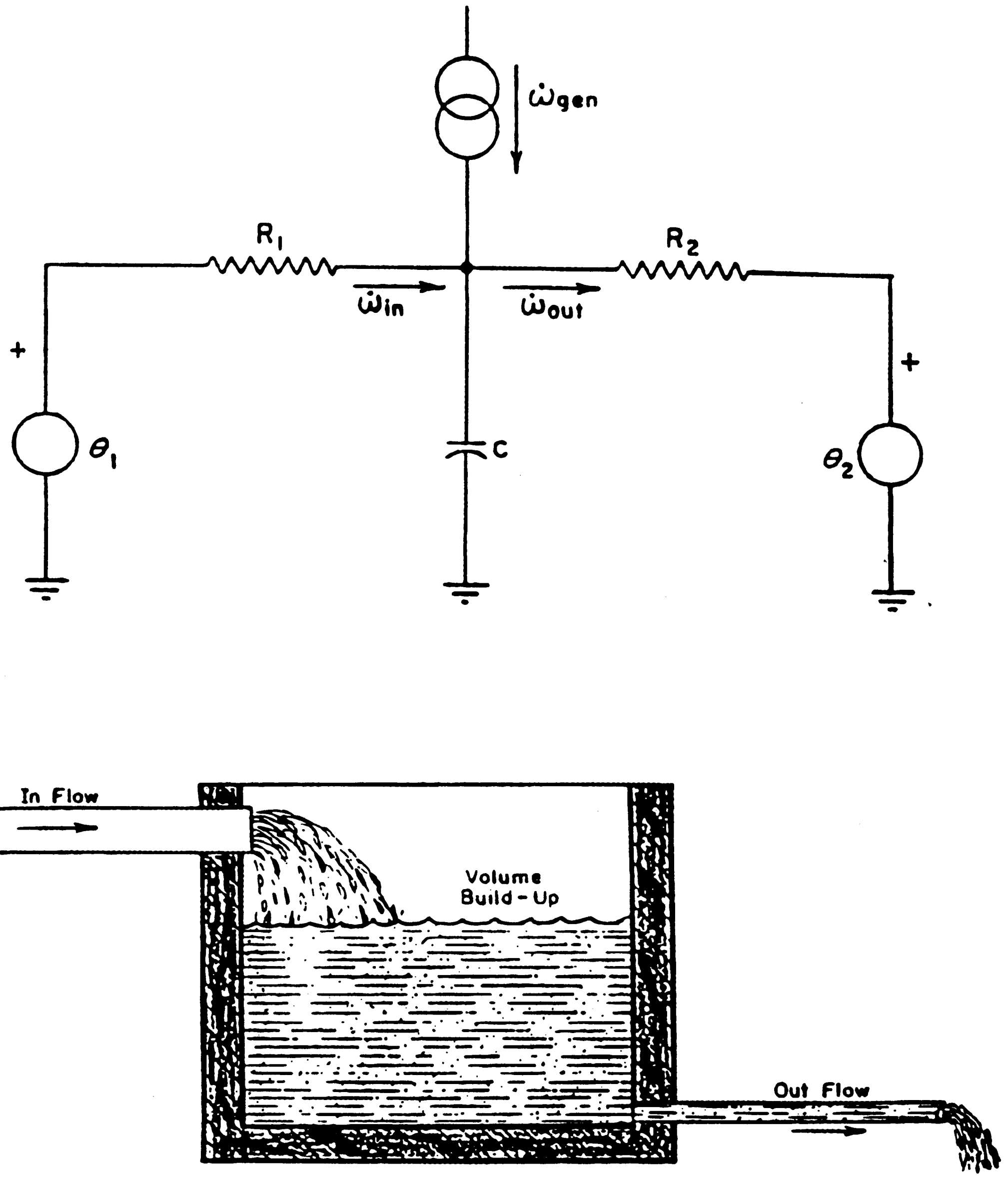


Fig. 4. Representations of an unsteady balance. At the top is a general systems representation with flow of a substance in, flow of the substance out, and generation of the substance contributing to the accumulation of the substance in a capacity element. Below is a fluid flow representation, where there is no fluid generation term. If the outflow is less than the inflow, the volume of the stored fluid will increase [8].

and compliances can then be determined. These are often nonlinear for biological materials. Lastly, reducing the empirical data to mathematical form has advantages of manipulation and condensed representation. Thus, a description of respiratory ventilation has now been given a conceptual framework, a basis in reality, and a mathematical description that can be related back to a concrete systems concept.

EXPERIENCES AT THE UNIVERSITY OF MARYLAND

The first course in biological transport processes at the University of Maryland uses the analogical systems approach. The course is taken by juniors, seniors, and graduate students with non-engineering backgrounds. Although these students have taken calculus through differential equations, there is an unenthusiastic attitude that they exhibit towards the use and understanding of the differential equations important in transport processes.

The first topic taught in this introductory transport processes course is the systems approach. Students are shown the differences between effort variables and flow variables; they are taught about resistance, capacity, inertia, time constants, and natural frequencies. They are introduced to the concepts of balances, and shown how these concepts can be applied in a general sense. Students are then asked to produce systems diagrams using the variables and parameters they have learned as applied to various medical and biological situations.

Students often have some initial difficulty with this section of the course. They are not used to dealing with a systems approach. They soon learn the distinctions between effort and flow variables, but have more trouble discriminating between sources and capacity elements.

For all the difficulties they have with these topics, however, they seem to have less trouble later conceptualizing fluids, heat, and mass transfer systems. Thus, it has been our experience that the 'concreteness' of this approach lends itself to familiarity in a reasonably short time.

Our graduate students take a follow-on course that is more theoretical, mathematically-based, and emphasizes coupled processes. This course emphasizes theory and model building, but does not include the design element that we expect in our undergraduate courses.

When designing our curriculum, we made the decision to expose students to the widest possible range of biological applications. Our thinking was that students interested in applications of engineering to biology should not have to choose a relatively narrow specialty at the undergraduate level. There is some choice of electives in our program, which does distinguish among interest areas, but all students are exposed to all applications, and there is a heavy emphasis on the basic biological sciences. The two most popular student interest areas are biomedical and bioenvironmental. All of these students attend the same required core courses and learn to deal with biological engineering applications in all interest areas.

Undergraduate students are taught how to use transport processes in such designs as sterilization systems for biomedical instruments, membrane selection for dialyses, and mechanical test systems for artificial hearts. Furthermore, because our biological engineering students have a wide range of applications interests, we give homework and design problems in environment, medicine, food, biotechnology, agriculture, and ecology. Homework problems are assigned weekly, and three major design problems dealing with fluid flow, heat transfer, and mass transfer, are assigned to all students in the course.

These design problems are equivalent to full-semester design problems assigned in other courses, but the students are given only 10 to 14 days to complete them. These are usually open-ended problems that allow students to do as much work as they can, and exercise insight, creativity, and imagination within a context of real-life constraints [14].

Students are given the problems verbally, not in a written form, and they are allowed to ask questions to help define the otherwise ambiguous assignments. If there are aspects that they do not ask about, they must still work the problems as best as they can. They soon learn to think about and anticipate the problems and formulate questions. Roles played in this process are consulting engineers (students), and a client (instructor), and non-technical verbal communication skills are exercised.

Students work homework assignments and design problems in groups of three or four. Many benefits accrue from this procedure, including cooperative learning, developing interpersonal skills, enhancement of communication and developing a sense of class cohesion and morale. Perhaps because of this, the general reaction of students to this course is that it is a lot of work, but one of the best classes they take.

When students complete the course they take with them many new or enhanced skills:

- the ability to conceptualize in a systems context;
- a new appreciation for the interface between the engineering and life sciences;
- an ability to deal with ill-defined biological engineering problems;
- an ability to acquire detailed knowledge about a new subject in a very short time;
- producing an acceptable design product from previous knowledge and experience;
- the ability to manage time, and to realize that some problems must be finished in a time that does not allow the absolutely best solution;
- written and verbal communications with people who don't always understand engineering jargon;
- writing in an organized and professional manner;
- peer-evaluation of others' reports;
- working within groups and depending upon others to meet deadlines;
- a better realization of engineering practice;
- self-confidence.

CONCLUSION

The field of medical and biological engineering has evolved to the point where everyone should be exposed to transport processes in their undergraduate years. The analogical systems approach, emphasizing similarities among transport processes and among different biological system scales, is an approach that can economize on the amount of new material that must be taught.

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