ENVIRONMENTAL BIOLOGY FOR ENGINEERS AND SCIENTISTS

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At the conclusion of this project, my feelings are well expressed by the last lines of *Huckleberry Finn*:

> *. . . and so there ain't nothing more to write about, and I am rotten glad of it, because if I'd 'a' knowed what a trouble it was to make a book I wouldn't 'a' tackled it, and I ain't a-going to no more.*

Dedicated to Liana and Carlo
D.A.V.

During the course of working on this book, and despite all the hours wrapped into its effort, my family learned a lot about the vital essence of life and the gifts we've all been given to share and treasure.

Dedicated to Carol, Amy, Matthew, Alison, Paul, and Elizabeth
J.E.A.

Dedicated to the environment, and to all those, past, present, and future, who make it worth caring about, especially to Daryl, Russell, Sue, Jean, and Arthur.
P.F.S.

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PREFACE

This book was originally developed to introduce environmental engineers to biology. However, we have realized that it will also fullfill a need for environmental scientists who specialize in nonbiological areas, such as chemists, physicists, geologists, and environmental planners. Much of what we say here about engineers applies also to these other specialists as well.

Those people coming from a biological science background might be surprised to discover that most engineers and many chemists and physicists do not have a single biology course in their bachelor's degree programs. Even environmental engineering students often receive only a brief exposure to sanitary microbiology, with a vast range of biological issues and concerns being neglected almost completely. Environmental chemists may study aquatic chemistry with little knowledge of biological activity in the aquatic system, and meteorologists studying global warming may have only a rudimentary understanding of the ecosystems that both affect and are affected by climate. However, the growth of the environmental sciences has greatly expanded the scope of biological disciplines with which engineers and scientists need to deal. With the possible exceptions of biomedical and biochemical engineering, environmental engineering is the engineering discipline that has the closest connection with biology. Certainly, it is the only engineering discipline that connects with such a wide range of biological fields.

The need to make engineers literate in biological concepts and terminology resulted in the development of a new graduate-level course designed to familiarize them with the concepts and terminology of a broad range of relevant biological disciplines. The first one-third of the semester introduced basic topics, covering each of the general biology topics in the first 10 chapters of the book. A college-level general biology text was used for this portion of the course, but no single text provided adequate coverage of the range of topics presented in the other chapters. This is the focus of and motivation for this book, which covers a much wider range of biology than has traditionally been taught to environmental engineers and scientists. Our intent in doing so is to strike off in a new direction with the approach to be used for training environmental professional in the future.

Specialists in every field have learned not to expect their colleagues trained in other areas to have certain basic knowledge in their own areas. This book aims to break one of these barriers of overspecialization. The objectives of a course based on this book will have been met if an engineer, chemist, or geologist who studied it is meeting with a biologist to discuss a situation of environmental concern, and the biologist at some point turns and says: ''How did you know that?'' It should not be a surprise that any well-educated person possesses some specialized knowledge outside his or her own profession.

The information herein is not limited to what environmental engineers or scientists ''need to know'' to do their jobs. The nonbiologist may occasionally need to read technical material written by biologists and should not be confused by the use of terminology standard to such material. Engineers and scientists who may eventually move to management positions of diversified organizations should be especially concerned about this.

A secondary need that this subject meets is the necessity for any technically literate person to be familiar with biology. Exposing nonbiologists to this field broadens their knowledge of the living world around them and of their own bodies. The biologically literate engineer or scientist will better understand and cope with the impact of technologically driven changes in the world. This understanding should encompass not only environmental issues such as pollution effects, ecosystem destruction, and species extinction, but also issues bearing on agriculture and medicine. Rapid progress in genetic engineering and medical technology makes it more essential to have such an understanding because it forces many societal and individual choices.

No single book can completely cover all biological topics relevant to environmental engineers and scientists. By design, this book has more information than could be covered in a single semester. Students should leave a course with a sense that there is more to know. It also gives students and instructors the choice of which topics to explore in more detail.

The first nine chapters are intended for use as a study guide and a summary of information that otherwise would have been learned in a course in general biology. Thus, they could be skipped in a course for, say, environmental science students who have already taken general biology. The rest of the chapters contain information that is specific to environmental applications. In broad terms, the important areas are traditional sanitary microbiology (health and biological treatment), ecology, and toxicology.

To play to the strengths of engineers, mathematical techniques are emphasized, as this was the initial focus of the book. Examples include population dynamics, microbial growth kinetics (focusing on batch systems, and stopping with the chemostat, short of treatment process models), pharmacokinetic models of toxicity, ecosystem modeling, statistical approaches to epidemiology, and probabilistic modeling of bioassay data. Other specialists, including biologists, could benefit from this treatment, as biology is becoming more and more quantitative. Nevertheless, the mathematical discussions can be skipped if time does not permit their development.

Familiarity with basic environmental concepts is assumed, such as the sources and types of pollutants, an understanding of acid–base relationships, oxygen demand, and other basic chemistry concepts.

There is sufficient information in this book for a two-semester course. We recognize that many programs have only a single semester to devote to this topic. Therefore, we offer the following as an outline on which to base such a course. The balance of the book will then be supplementary and reference material that instructors may draw from based on their special interests. The instructor may also consider assigning a research paper to be based on a topic from the book not included in the course.

Topic	Chapters/Sections
1. **Introduction**: the study of biology; complexity; ethics; biological hierarchies, evolution, taxonomy, interactions in biology	Chaps. 1 and 2
2. **Biochemistry**: organic structure and physicochemistry, carbohydrates, proteins, lipids, nucleotides **The cell**: structure and function, membranes	Chaps. 3 and 4
3. **Metabolism**: enzyme kinetics, glycolysis, fermentation, respiration	Secs. 5.1–5.3, 5.4.1–5.4.3
4. **Genetics**: heredity, DNA replication, protein synthesis, mutations and DNA repair, polymerase chain reaction	Secs. 6.1.1, 6.2, 6.3
5. **Plant and animal taxonomy**: including the fungi **Human physiology**: respiratory system, endocrine system, excretory system	Secs. 7.1, 8.1, 8.4.2, 9.1, 9.8, 9.11, 9.12
6. **Microbes**: stoichiometry, metabolism, classification, pathogenesis	Chaps. 10, 12
7. **Microbial growth kinetics**	Chap. 11
8. **Biogeochemical cycles**: nitrogen cycle reactions, etc.	Chap. 13
9. **Ecology**: energy pyramid, food web, biogeochemical cycles, population growth, diversity	Chap. 14
10. **Ecosystems**: forest, soil, aquatic, wetlands, microbial	Secs. 15.1–15.3, 15.5
11. **Biological pollution control**: activated sludge, anaerobic digestion	Chap. 16
12. **Toxicology**: mechanisms, effects, carcinogens, organ effects	Chap. 17
13. **Fate and transport**: uptake, absorption, distribution, biotransformation, excretion	Secs. 18.1–18.6
14. **Dose–response**: extrapolation, toxicity testing	Secs. 19.1–19.4, 20.1
15. **Toxicity**: effects of specific substances	Secs. 21.1–21.4

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D. A. VACCARI

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PERSPECTIVES ON BIOLOGY

Before immersing ourselves in the subject of environmental biology, in this chapter we consider factors to motivate, facilitate, and provide a context for that study. Thus, we start by discussing reasons, history, mindsets, and ethics that can guide our approach to the subject.

1.1 WHY ENVIRONMENTAL ENGINEERS AND SCIENTISTS SHOULD STUDY BIOLOGY

For an environmental scientist, the answer to the question posed in the title of this section is fairly evident. However, for environmental engineers it is worthwhile to consider this in more detail. For example, environmental engineers need to know a broader range of science than does any other kind of engineer. Physics has always been at the core of engineering, and remains so for environmental engineers concerned with advective transport (flow) in the fluid phases of our world. The involvement of environmental engineers with chemistry has increased. Formerly, it was limited to chemical precipitation and acid–base chemistry in water, and relatively simple kinetics. Now it is necessary also to consider the thermodynamics and kinetics of interphase multimedia transport of organics, the complex chain reaction kinetics of atmospheric pollutants or of ozone in water, and the organic reaction sequences of pollutant degradation in groundwater. In a similar way, the role of biology in environmental engineering has burgeoned.

Traditionally, the biology taught to environmental engineers has emphasized microbiology, because of its links to human health through communicable diseases and due to our ability to exploit microorganisms for treatment of pollutants. Often, there is a simple exposure to ecology. However, the ecology that is taught is sometimes limited

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to nutrient cycles, which themselves are dominated by microorganisms. As occurred with chemistry, other subspecialties within biology have now become important to environmental engineering. Broadly speaking, there are three main areas: microbiology, ecology, and toxicology. The roles of microbiology are related to health, to biological pollution control, and to the fate of pollutants in the environment. Ecological effects of human activity center on the extinction of species either locally or globally, or to disturbances in the distribution and role of organisms in an ecosystem. Toxicology concerns the direct effect of chemical and physical pollutants on organisms, especially on humans themselves.

This book aims to help students develop their appreciation for, and awareness of, the science of biology as a whole. Admittedly, applied microbiology is often included in many environmental engineering texts, focusing on disease transmission, biodegradation, and related metabolic aspects. However, little if any material is provided on the broader realm of biology in relation to environmental control. Such an approach notably overlooks a considerable number of important matters, including genetics, biochemistry, ecology, epidemiology, toxicology, and risk assessment. This book places this broad range of topics between two covers, which has not been done previously.

There are other factors that should motivate a study of biology in addition to the practical needs of environmental engineers and scientists. The first is the need to understand the living world around us and, most important, our own bodies, so that we can make choices that are healthy for ourselves and for the environment. Another is that we have much to learn from nature. Engineers sometimes find that their best techniques have been anticipated by nature. Examples include the streamlined design of fish and the countercurrent mass-transfer operation of the kidney. An examination of strategies employed by nature has led to the discovery of new techniques that can be exploited in systems having nothing to do with biology. For instance, the mathematical pattern-recognition method called the *artificial neural network* was inspired by an understanding of brain function. New process control methods are being developed by reverse-engineering biological systems. Furthermore, there may be much that engineers can bring to the study of biological systems. For example, the polymerase chain reaction technique that has so revolutionized genetic engineering was developed by a biologist who was starting to learn about computer programming. He borrowed the concept of iteration to produce two DNA molecules repeatedly from one molecule. Twenty iterations quickly turn one molecule into a million.

Engineers can also bring their strengths to the study of biology. Biology once emphasized a qualitative approach called **descriptive biology**. Today it is very much a quantitative science, using mathematical methods everywhere, from genetics to ecology. Finally, it is hoped that for engineers the study of biology will be a source of fascination, opening a new perspective on the world that will complement other knowledge gained in an engineering education.

1.2 PRESENT PERSPECTIVES ON ENVIRONMENTAL ENGINEERS AND SCIENTISTS

Science is defined as "knowledge coordinated, arranged, and systematized" (Thatcher, 1980). The *McGraw-Hill Dictionary of Science and Engineering* (Parker, 1984) defines **engineering** as "the science by which the properties of matter and the sources of power in nature are made useful to humans in structures, machines, and products."

Thus, engineering is defined as one of the sciences. Yet in the professional world, those who classify themselves as scientists and those who call themselves engineers seem to distinguish themselves from each other. To be sure, engineers study the sciences relevant to their disciplines, although not as deeply as scientists might prefer (the subject of this book being an instance of this). On the other hand, wouldn't scientists benefit from a better understanding of how to apply engineering analysis to their fields? For example, aren't mass and energy balances or transport phenomena useful for analyzing the multiplicity of phenomena affecting a laboratory experiment?

The following comparison of engineers' and scientists' approaches were obtained from the authors' observations, plus informal discussions with science and engineering practitioners. They reflect the perception of differences between engineers and scientists, not necessarily reality. They certainly do not apply to all. A common complaint to be heard from a scientist about an engineer is that the latter ''wants to reduce everything to a number'' and tends not to look at the system holistically. This may be due to the basic function for which an engineer is trained—to **design**: that is, to create an arrangement of matter and energy to attain a goal or specification, using the minimum amount of resources. Ultimately, this is reduced to such things as how big, how much, or for how long an arrangement must be made. An engineer designing an in situ groundwater bioremediation project uses models and design equations (and judgment) to determine flow rates, well locations, nutrient dosages, duration of treatment, and finally, the financial resources needed to eliminate a subsurface contaminant.

However, nonquantitative factors may be just as important to the success of a project. Are microorganisms present that are capable of utilizing the contaminant? In fact, is the contaminant biodegradable at all? Are the by-products of the biodegradation process more or less toxic than the starting material? Although such considerations are taught in engineering courses, a quick look at homework and exams shows that the emphasis is on the ''single-valued outcome,'' the bottom-line answer.

Paradoxically, there is also a sense in which an engineer's approach is *more* holistic than a scientist's. To make a problem tractable, the scientist may simplify a system, such as by considering it as a *batch* or *closed system*: one in which material cannot cross the boundary. Alternatively, a scientist may restrict systems to be either constant temperature or adiabatic (insulated): a reaction in a beaker, microbial growth in a petri dish, or a laboratory ecosystem known as a **microcosm**. An engineer deals more often with flow or open systems. He or she will literally turn on the pump, adding and removing material and energy. The underlying process is the same from a scientist's point of view. However, the study of open systems is dealt with much more often in engineering courses than in science courses. This study enables scientific principles to be applied more directly to real problems in industrial or environmental situations.

An engineer may be more likely to draw conclusions inductively from previous cases to find solutions to a problem. On the other hand, a scientist prefers to avoid assumptions and to base decisions on case-specific information only. For example, in examining a contaminated landfill, an engineer expects it to be similar to others in his or her experience, until information to the contrary appears. A scientist may be more deductive and may be reluctant to proceed until a thorough study has been conducted. The former approach is more economical, except when unanticipated problems arise. The latter approach is more rigorous but may sometimes be impractical because of cost. One must decide between the risk of overlooking unexpected problems vs. that of experiencing ''paralysis by analysis.''

A scientist is looking for knowledge; an engineer is looking for solutions. Thus, when an engineer is done with his or her work, a problem has been solved. When a scientist is done, there may be more questions than before.

Engineers are trained to consider the cost-effectiveness of their actions. Economic feasibility may be farther down the list of a scientist's priorities. Some engineers are more willing to make environmental trade-offs; an environmental scientist prefers to ''draw the line'' against any environmental costs. If wetlands would be destroyed by a project, an engineer may weigh it against the value of the project. If the project is important enough, the value of the wetlands may be compensated for by mitigation or by replacement methods. A scientist may accept the necessity of this, but may still consider the loss of the original wetlands a tragedy.

The tasks of both scientists and engineers are to explain (analyze), predict (forecast), and prescribe (design). A scientist needs to know about all of the individual phenomena that may affect a system and how they are related. An engineer often depends on having a mathematical model to represent the phenomena. If such a model can be created, engineers can produce quantitative results. However, science comes into play again when the limitations of the model are considered. These include extreme conditions where assumptions of the model may be violated and effects of phenomena (and every system will have such phenomena) that are not amenable to mathematical modeling.

For example, suppose that an industry that uses well water from a shallow aquifer is having problems with iron in the water. After use, the water is contaminated with biodegradable organics and ammonia and is treated in a lagoon system before discharge to surface water. In considering the pollutional inputs to the system and an analysis of the groundwater, a scientist, might identify the problem as being due to a recycling effect where some of the water seeps from the lagoon into the soil, whereupon microbially mediated nitrification consumes some of the alkalinity in the water, lowering the pH, dissolves iron from the soil, and then is again taken up in the well. The scientist might then prescribe a long-term solution involving adding alkalinity to the water after use. An engineering approach might be to model the system using acid–base chemistry to predict the effect of the nitrification on the effluent, followed by groundwater flow and water quality modeling to predict the water quality at the well. The model could be used to determine the alkalinity dosage required, leading to a design for the treatment process.

This process started with a scientific analysis and continued with engineering methods. Now, suppose further that after implementation, the lagoon effluent being discharged to the surface water is found toxic to fish. Again, a scientific analysis is called for: a toxicity identification evaluation (TIE). It may be found that at the higher pH, more of the ammonia in the effluent is in non-ionized form, which is more toxic to fish than is the ammonium ion. No one will doubt that science and engineering cannot be divorced from each other, but the better that engineers and scientists understand each other's disciplines, the better the outcome will be.

The engineering approach can be fruitful for scientific inquiry. Consider the problem of explaining why multicellular life-forms evolved. A biologist may think first of survival, fitness, and adaptation. An engineering approach might focus on considerations of energy efficiency and the effect of area/volume ratio on mass and energy transfer between the organism and the environment. Both approaches are valid and contribute to understanding.

Engineers and scientists have much to learn from one another, which they do by working together. In addition, both will profit from a direct study of each other's disciplines.

There are many instances in this book of mathematical or engineering analysis applied to biology. These should help convince engineers that biology really is a "hard" science. By learning and applying knowledge of biology, engineers can help convince scientists that engineering isn't always simplification and abstraction—that they can take into account the full complexity of a system. At the same time, engineers should be humble about their capability. The following statement by LaGrega et al. (2001) with respect to toxicology should be true of other biological disciplines as well: "What is the single, most important thing for an engineer to know about toxicology? The engineer cannot and should not practice toxicology." Still, the more the nonspecialist understands, the better his or her decision making will be.

1.3 PAST PERSPECTIVES ON ENVIRONMENTAL ENGINEERS AND SCIENTISTS

Environmental biology is not a unified discipline. Almost every chapter in this book could constitute a different field with its own history. What we can describe here is a bit of history of the development of the associations that have formed between biology and environmental engineers.

Barely a century ago, environmental and sanitary issues were largely the domain of scientists rather than engineers. In fact, long before the practice of environmental engineering had ever been conceived, physicists, chemists, and biologists were already hard at work investigating a range of pollution problems that they recognized as a serious threat.

These sorts of concerns about procuring clean waters and discarding wastes safely had actually been documented and addressed for at least two millennia. However, by the time that Charles Dickens had written his classic, *A Tale of Two Cities*, the "worst of times" had truly befallen most industrialized countries. Humankind's waste emissions had finally overtaxed nature's assimilatory capacity, and the telltale signs were readily evident. Skies were blanketed with coal smoke and soot, rivers were befouled with a sickening blend of filth, and waste piles offered frightful opportunities for the dissemination of disease.

In the latter half of the nineteenth century, the heightened level of pollution brought by the Industrial Revolution triggered a response from scientists, whose contributions continue to this day. For example, one of England's leading chemists, Edward Frankland, routinely monitored water quality changes in the Thames River, and his microbiologist son, Percy, tried to resolve the bacterial reactions found in sewage. John Tyndall, a renowned physicist, focused a considerable amount of his talent on air quality and contaminant analysis problems. Charles Darwin's eminent friend and staunch supporter, Thomas Huxley, played a major role in the cause of sanitary reformation as a practical extension to his expertise in biology.

The roots of our modern practice of environmental engineering sprang largely from the sciences. These investigators were not motivated by regulatory requirement, legal threat, or financial gain. Instead, their fledgling efforts were effectively compelled by personal concerns about an environment whose quality had already deteriorated seriously. These scientists had been trained to appreciate the balance of nature and were duly concerned about the stress imposed by a rapidly escalating range of pollution problems. It was the field of biology, however, which truly gave these yesteryear environmental efforts their highest motivation. Biologists working at the end of the nineteenth century demonstrated successive refinements in their sense of awareness and appreciation for the technical importance of the environmental problems that they faced.

The connection between biology and environmental engineering is best demonstrated by tracing the academic lineage extending beyond Thomas Huxley's seminal work with sanitary health. Although apparently self-educated, Huxley was a preeminent leader in the emerging field of biology late in the nineteenth century and gained worldwide recognition for his forceful backing of Charles Darwin's evolutionary theories. Having been invited to present the opening speech for Johns Hopkins University's inaugural ceremony in 1894, he used the opportunity to recommend one of his students H. Newell Martin, as chairman of the first biology department in the United States. Under Martin's leadership, students were imbued with an inherent sense of "environmental" concern. For William Sedgwick, this issue became a lifelong cause. After receiving his doctorate, Sedgwick joined the biology program at Harvard, where he introduced a radical new focus on sanitary matters. Together with his own student, George Whipple, he then cofounded public health programs at Harvard and the Massachusetts Institute of Technology (MIT), which in the coming years would lead formatively to distinct academic offerings in public health, sanitation, and industrial hygiene. At much the same time, Sedgwick and Whipple created a technical program at MIT that dealt with the applied aspects of sanitary science, thereafter known as the first-ever environmental engineering program.

1.4 AMBIGUITY AND COMPLEXITY IN BIOLOGY

Often in fields such as physics or engineering it is possible to identify all the variables that affect a process (in terms of a model). In fact, the number of variables can be reduced to a minimum by the use of dimensional analysis, producing a set of dimensionless numbers that describe a situation completely. In biology, it is more common for there to be unknown influences and obvious gaps in our knowledge. Consequently, many biological "facts" are conditional—answers often have to be prefaced with "it depends..." or important questions may be totally lacking an answer. Despite the recent explosion of knowledge in chemical genetics, we still cannot give a satisfactory explanation of how an embryonic cell "knows" to grow into part of a fingertip and not a hair follicle. We need to have a certain humility in our studies:

> In school we start each course at the beginning of a long book full of things that are known but that *we* do not yet know. We understand that beyond that book lies another book and that beyond that course lies another course. The frontier of knowledge, where it finally borders on the unknown, seems far away and irrelevant, separated from us by an apparently endless expanse of the known. We do not see that we may be proceeding down a narrow path of knowledge and that if we look slightly left or right we will be staring directly at the unknown. (Gomory, 1995)

Few appreciate the difficulty of making ironclad distinctions in the study of biology. Actually, the same is true for all fields, although it is perhaps more apparent in biology. In engineering, the mathematical constructions create an abstract ideal out of concepts. When we speak of the velocity of water in a pipe, the idea seems very clear and can be manipulated fairly unambiguously, such as to compute flow or pressure drop. However,