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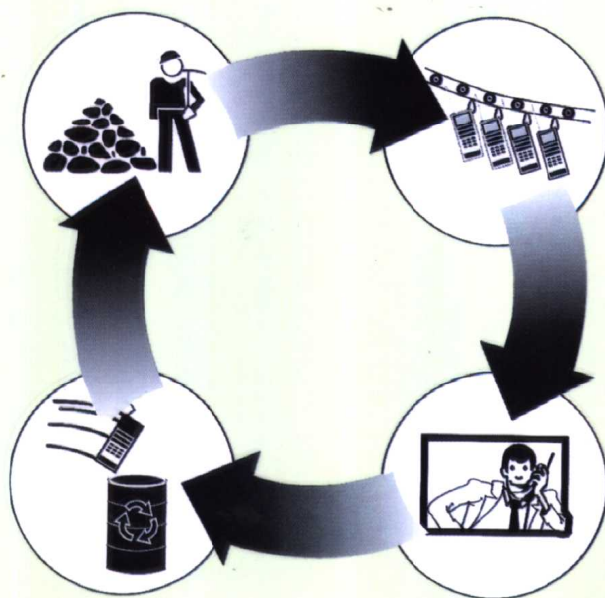
T. E. Graedel B. R. Allenby

# Industrial Ecology

(Second Edition)

## 产业生态学

(第2版)



Pearson  
Education

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# 出版前言

在 21 世纪初，面临各种环境问题，人类清醒地认识到要走可持续发展之路。而发展环境教育是解决环境问题和实施可持续发展战略的根本。高等学校的环境教育，是提高新世纪建设者的环境意识，并向社会输送环境保护专门人才的重要途径。为了反映国外环境类教材的最新内容和编写风格，同时也为了提高学生阅读专业文献和获取信息的能力，我们精选了一些国外优秀的环境类教材，组成大学环境教育丛书影印版和翻译版，本书即为其中的一册。所选教材均在国外被广泛采用，多数已再版，书中不仅介绍了有关概念、原理及技术方法，给出了丰富的数据，还反映了作者不同的学术观点。

我们希望这套丛书能对高等院校师生和广大科技人员有所帮助，同时为我国环境教育的发展作出贡献。

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2004 年 1 月

*In memory of Robert A. Laudise*  
*Enthusiast and supporter of industrial ecology*

# Preface

It has been a maxim of many years' standing that the goals of industry are incompatible with the preservation and enhancement of the environment. It is unclear whether that maxim was ever true in the past, but there is certainly no question that it is untrue today. The more forward-looking corporations and the more forward-looking nations recognize that providing a suitable quality of life for Earth's citizens will involve not less industrial activity but more, not less reliance on new technologies but more, not less interaction of technology with society but more, and that providing a sustainable world will require close attention to industry-environment interactions. This awareness of corporations, of citizens, and of governments promises to ensure that corporations that adopt responsible approaches to industrial activities will not only avoid problems but will benefit from their foresight.

Indeed, the involvement of industry is crucial if the world is to achieve sustainable development. Robert Sievers of the University of Colorado points out that governments have many critical short-term issues demanding their attention: achieving economic stability, feeding growing populations, establishing politically viable nations, making the transition from centrally controlled to free market economies, and so forth. The activities of many governments may thus be rather insular for the foreseeable future. At the same time, corporations are increasingly multinational, have longer time horizons, and depend for their survival and prosperity on relatively stable global business conditions and on responding to the desires and concerns of many different cultures and populations. Private firms, not governments, choose, develop, implement, and understand technology. Hence, responsible corporations may turn out to be among the global leaders in the transition between nonsustainable and sustainable development, but they will need the help of governments and nongovernmental organizations in establishing broad, insightful approaches and frameworks to the complex interactions that are involved.

There are three time scales of significance in examining the interactions of industry and environment. The first is that of the past, and concerns itself almost entirely with remedies for dealing with inappropriate disposal of industrial wastes. The second time scale is that of the present, and deals largely with complying with regulations, with preventing the obvious mistakes of the past, and with conducting responsible operations. Hence, it emphasizes waste minimization, avoidance of known toxic chemicals, and “end-of-pipe” control of emissions to air, water, and soil. Corporate environment and safety personnel are often involved, as are manufacturing personnel, in making small to modest changes to processes that have proved their worth over the years. On neither of these time scales do today’s industrial process designers and engineers play a significant role.

The third time scale is that of the future. The industrial products, processes, and services that are being designed and developed today will dictate a large fraction of the industry–environment interactions over the next few decades. Thus, process and product design engineers hold much of the future of industry–environment interactions in their hands, and nearly all are favorably disposed toward doing their jobs with the environment in mind.

Their problem is that doing so requires knowledge and perspective never given to them during their college or professional educations and not readily available in their current positions. Remediating this situation for the students and technological professionals of today and tomorrow is the primary focus of this book. In addition, we have crafted the book so that it will be a useful addition to curricula in policy, business, environmental science, law, and other related specialties, since it is equally important that students and professionals in those disciplines understand more about technology’s role in mitigating or contributing to environmental problems.

Industrial ecology, which we define in Chapter 2, is a modern approach to thinking about economy–environment interactions. As applied to manufacturing, it requires familiarity with industrial activities, environmental processes, and societal interactions, a combination of specialties that is rare. Accordingly, we have purposely attempted to make this volume useful for those whose primary background is industrial, environmental, or societal, or for those who interact with specialists in those disciplines. Many chapters include discussions of common industrial approaches to the issue being discussed as well as perspective on the environmental impacts produced. For the latter, we emphasize impacts on long time and space scales, as shorter horizons are often better recognized and better regulated either internally or externally. The approaches differ depending on the venue, but all in all, industrial ecology is about ways to transform environmental goals into reality.

The book is divided into five sections. The first provides a brief definition of the topic and outlines the approach of the book. The second, the Physical, Biological, and Societal Framework, describes the playing field on which industrial ecology operates, and the opportunities and constraints that each of these areas provides. In the third section, Design for Environment, topics central to the designers of products, processes, and services are discussed: energy, materials, product delivery and use, end of life. The central concept of life-cycle assessment is introduced here in some detail. The fourth section, Corporate Industrial Ecology, addresses the implementation of industrial ecology within the corporate environment. The final section, Systems-Level Industrial Ecology, deals with issues broader than a design, a factory, or a corporation, as we discuss industrial ecosystems, resource analysis, models and predictions, and Earth system science and engineering.

We have purposely mixed the philosophical with the practical. Avoiding that mix creates a textual product that is easier to write and easier to comprehend, but one that is much less relevant. The essence of industrial ecology is that it is the combination of technology with society, and that combination has many facets and many implications. The industrial ecologist needs to appreciate corporate and societal interactions, and to understand something of the interactions of industrial activity with the environment. Only at that point is there a logical framework in which to place goals and techniques.

We have been gratified at the reception given to the first edition of this book. It was published in 1995, at a time when industrial ecology was a young field searching for definition, approaches, and tools. Our attempt to fill this need was inevitably preliminary. Nonetheless, several thousand students and professionals used the book; Sukehiro Gotoh of Japan's National Institute for Research on the Environment translated it into Japanese; and several thousand students and professionals acquired our subsequent books, *Design for Environment* (1995), *Industrial Ecology and the Automobile* (1998), *Streamlined Life-Cycle Assessment* (1998) (T.E.G. only), and *Industrial Ecology: Policy Framework and Implications* (1999) (B.R.A. only), all published by Prentice Hall. During these few years, the field has begun its own archival publication, the *Journal of Industrial Ecology*, and has formed the International Society of Industrial Ecology. The vigor and lasting nature of industrial ecology is now unmistakable.

As industrial ecology has developed, ideas that were embryonic a decade ago have matured, and new ways of approaching technology–environment interactions have emerged. Accordingly, we spend significant parts of this edition of the book on topics completely unaddressed in the first edition: the relevance of biological ecology, indicators and metrics, the service sector, industrial symbiosis, systems analysis, and scenario development, to name a few. In a textbook for a mature field, these additions would be largely a synthesis of the work of many. Industrial ecology is new enough and its practitioners few enough, however, that parts of these topics represent our efforts to define and describe areas not yet widely addressed, but appearing to hold considerable promise. These new areas seem likely to transform industrial ecology from a topic centered rather narrowly on product design to one defining the parameters and pathways toward sustainable development. In the process, industrial ecology is becoming increasingly interdisciplinary and ever more broadly relevant.

We are grateful to many people for their help during the preparation of this second edition. Detailed reviews were performed by Arpad Horvath, University of California, Berkeley, Timothy Considine, Pennsylvania State University, M. Bertram, R. Gordon, R. Lifset, H. Rechberger, and S. Spatari, and the book is much the better for their comments. For the use of illustrations and examples, we thank I. Horkeby (Volvo Car Corporation), and R. Tierney (Pratt & Whitney). We have appreciated our interactions with the staff at Prentice Hall, especially Marcia Horton and Laura Fischer, who have helped us produce what we feel is a most attractive book. Finally, we thank AT&T, the AT&T and Lucent Foundations, the U.S. National Science Foundation, and the U.S. National Academy of Engineering for their support of industrial ecology initiatives; their help has been essential in the development of this new field.

T. E. GRAEDEL  
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# PART I     Introducing the Field

## C H A P T E R   1

# Humanity and Environment

### 1.1     THE TRAGEDY OF THE COMMONS

In 1968, Garrett Hardin of the University of California, Santa Barbara, published an article in *Science* magazine that has become more famous with each passing year. Hardin titled his article “The Tragedy of the Commons”; its principal argument was that a society which permitted perfect freedom of action in activities that adversely influenced common properties was eventually doomed to failure. Hardin cited as an example a community pasture area, used by any local herdsman who chooses to do so. Each herdsman, seeking to maximize his financial well-being, concludes independently that he should add animals to his herd. In doing so, he derives additional income from his larger herd but is only weakly influenced by the effects of overgrazing, at least in the short term. At some point, however, depending on the size and lushness of the common pasture and the increasing population of animals, the overgrazing destroys the pasture and disaster strikes all.

A modern version of the tragedy of the commons has been discussed by Harvey Brooks of Harvard University. Brooks points out that the convenience, privacy, and safety of travel by private automobile encourages each individual to drive to work, school, or stores. At low levels of traffic density, this is a perfectly logical approach to the demands of modern life. At some critical density, however, the road network commons is incapable of dealing with the traffic, and the smallest disruption (a stalled vehicle, a delivery truck, a minor accident) dooms drivers to minutes or hours of idleness, the exact opposite of what they had in mind. Examples of frequent collapse of road network commons systems are now legendary: Los Angeles, Tokyo, Naples, Bangkok, Mexico City.