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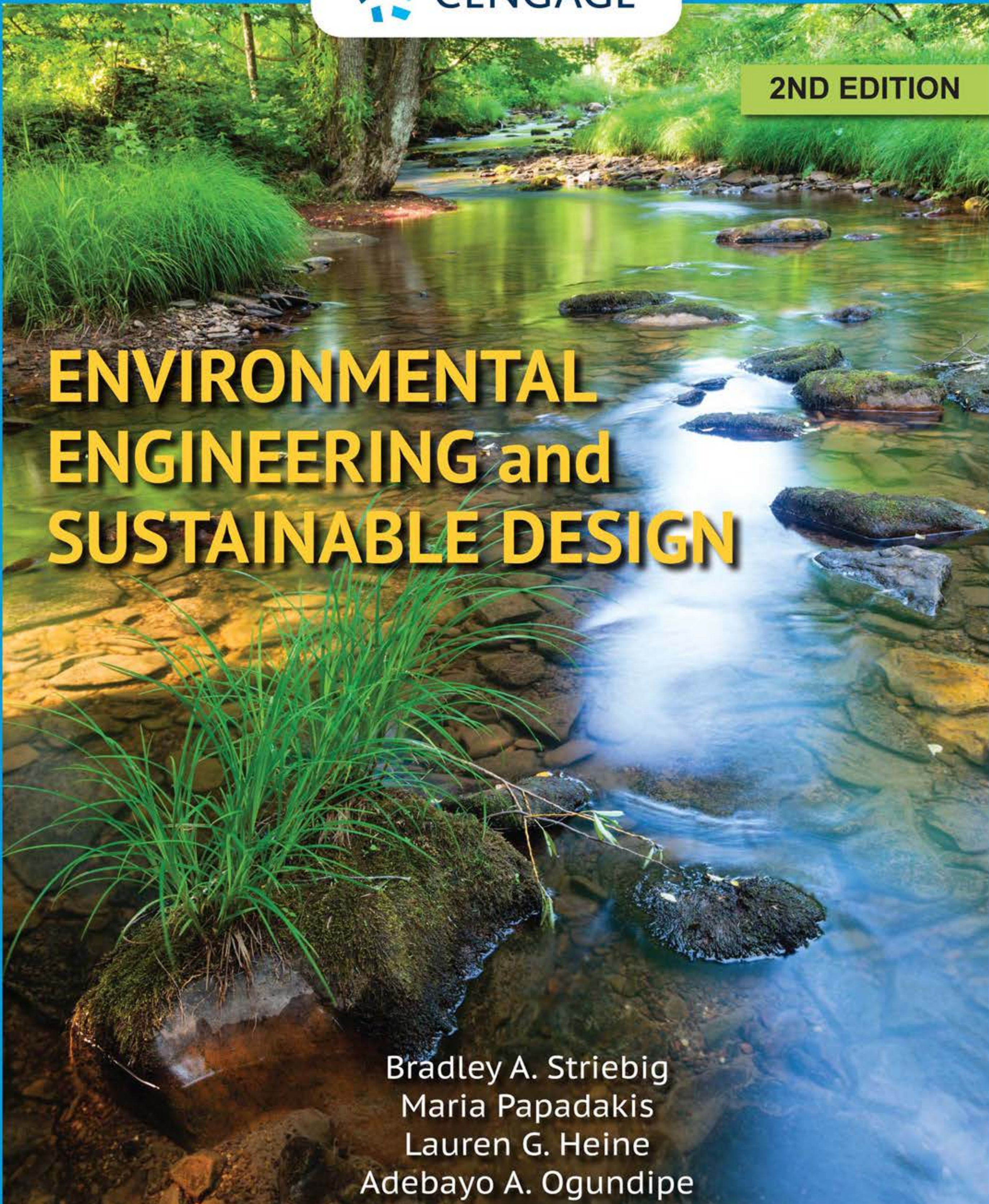

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Environmental Engineering and Sustainable Design

SECOND EDITION

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***Environmental Engineering and Sustainable Design,* Second Edition**
Bradley A. Striebig, Maria Papadakis, Lauren G. Heine, and Adebayo A. Ogundipe

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For Echo and Zachary

—Bradley A. Striebig

In memory of Pete Papadakis

—Maria Papadakis

In memory of P. Aarne Vesilind

—Lauren G. Heine

To all my Teachers

—Adebayo A. Ogundipe

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Part 2 ENGINEERING ENVIRONMENTAL AND SUSTAINABLE PROCESSES

Preface

Environmental Engineering and Sustainable Design, Second Edition is an invaluable resource for today's engineering and applied environmental science students. As engineering curriculum becomes more crowded, challenges arise in addressing the new paradigm of engineering in a resource-limited environment and adapting design to a new climactic condition. The authors have developed a comprehensive text that provides foundational knowledge and traditional engineering skills while also integrating our present understanding of resource consumption and climate issues into this new edition. This curriculum is focused upon applying engineering principles to real-world design and problem analysis. It includes specific step-by-step examples and case studies for solving complex conceptual and design problems related to sustainable design and engineering. This textbook also applies the principles of sustainable design to issues in both developed and developing countries. Instructors will benefit from having this updated best seller to bring sustainability science, environmental impact analysis, and models of sustainability to the undergraduate and graduate level.

Sustainability is important in manufacturing, construction, planning, and design. Allenby et al. state that: "Sustainable engineering is a conceptual and practical challenge to all engineering disciplines." The teaching of sustainability has sometimes been pigeonholed into graduate level courses in Industrial Ecology or Green Engineering. Environmental engineering and chemical engineering textbooks may cover some basic concepts of sustainability, but the extent and breadth of knowledge is insufficient to meet the multifaceted demand required to engineer sustainable processes and products.

Dr. John Crittenden, 2002, suggests that sustainable solutions include the following important elements/steps: (a) translating and understanding societal needs into engineering solutions such as infrastructures, products, practices, and processes; (b) explaining to society the long-term consequences of these engineering solutions; and (c) educating the next generation of scientists and engineers to acquire both the depth and breadth of skills necessary to address the important physical and behavioral science elements of environmental problems and to develop and use integrative analysis methods to identify and design sustainable products and systems.

New to the Second Edition

The Second Edition has been expanded to appeal to traditional foundational environmental engineering courses.

The content has been organized into three key sections:

- Part I: Environmental and Sustainability Science Principles
- Part II: Engineering Environmental and Sustainable Processes
- Part III: Designing Resilient and Sustainable Systems

Significant content from this textbook is adapted from *Introduction to Environmental Engineering,* Third Edition by P. Aarne Vesilind, Susan M. Morgan, and Lauren G. Heine. This content expands the use of the textbook to traditionally taught environmental engineering courses. This text is also used in courses focused on sustainable design and engineering, and this update provides content that is suitable to teaching a course on climate adaptation and resilience, as illustrated in Table P.1.

Topics new or significantly expanded in this edition include:

- Chapter 4: Material Flow and Processes in Engineering
- Chapter 5: Natural Resources, Materials, and Sustainability
- Chapter 6: Hazardous Substances and Risk Assessment
- Chapter 8: Wastewater Treatment
- Chapter 11: Energy Conservation, Development, and Decarbonization
- Chapter 12: Designing for Sustainability
- Chapter 15: Assessing Alternatives

New homework problems have been added and integrated into this textbook. Each chapter includes both qualitative and quantitative problems that cover a range of difficulty and complexity. Additional Active Learning Exercises have been added, with a focus on peer-to-peer learning activities to stimulate discussion, including the incorporation of climate and energy simulations for group role playing activities.

Organization and Potential Syllabus Topics

Sustainability is most often covered in existing environmental engineering courses; however, these courses are typically limited to civil and environmental engineering majors. Introductory environmental engineering courses often have objectives focused more upon historical perspectives in remediation and large-scale treatment systems than upon forward-looking sustainability concepts. Students will benefit from having methods for quantifying sustainability through environmental impacts, case studies, Life Cycle Analysis (LCA) models, and best practices. Case studies and active learning exercises make the learning experience real-world and hands-on. This title is the first to bring sustainability science, environmental impact analysis, and models of sustainability to the undergraduate level. Prerequisites for such a course are the foundational courses in calculus, chemistry, and physics.

Environmental Engineering and Sustainable Design, Second Edition is clearly arranged in three parts. *Part I: Environmental and Sustainability Science Principles* includes foundational content in the physical and social sciences that describe sustainability. *Part II: Engineering Environmental and Sustainable Processes* describes processes that relate to understanding and creating more sustainable systems for water development, air quality, climate adaptation, and energy development. *Part III: Designing Resilient and Sustainable Systems* addresses new tools and models that can be used in the design of products and infrastructure to create systems adapted to living in a resource-limited world that requires more sustainable approaches to the lifestyle of the developed world's nations. Suggested topics for courses are shown in Table P.1.

TABLE P.1 Suggested topics for courses in environmental engineering, sustainable design and engineering, and climate adaptation and resilience. New or reorganized chapters are bolded

CHAPTER	ENVIRONMENTAL ENGINEERING	SUSTAINABLE DESIGN AND ENGINEERING	CLIMATE ADAPTATION AND RESILIENCE
PART I: ENVIRONMENTAL AND SUSTAINABILITY SCIENCE PRINCIPLES			
Ch. 1 Sustainability, Engineering, and Design	X	X	X
Ch. 2 Analyzing Sustainability Using Engineering Science	X		X
Ch. 3 Biogeochemical Cycles	X		X
Ch. 4 Material Flow and Processes in Engineering	X		
Ch. 5 Natural Resources, Materials, and Sustainability	X	X	X
Ch. 6 Hazardous Substances and Risk Assessment	X		
PART II: ENGINEERING ENVIRONMENTAL AND SUSTAINABLE PROCESSES			
Ch. 7 Water Quality Impacts	X		
Ch. 8 Wastewater Treatment	X		
Ch. 9 Impacts on Air Quality	X		
Ch. 10 The Carbon Cycle and Energy Balances	X	X	X
Ch. 11 Energy Conservation, Development, and Decarbonization		X	X
PART III: DESIGNING RESILIENT AND SUSTAINABLE SYSTEMS			
Ch. 12 Designing for Sustainability		X	X
Ch. 13 Industrial Ecology		X	
Ch. 14 Life Cycle Analysis		X	
Ch. 15 Assessing Alternatives		X	X
Ch. 16 Sustainability and the Built Environment		X	X
Ch. 17 Challenges and Opportunities for Sustainability in Practice		X	X

Supplements

Additional instructor resources for this product are available online. Instructor assets include a Solution Answer Guide, Image Library, and PowerPoint® slides. Sign up or sign in at www.cengage.com to search for and access this product and its online resources.

Acknowledgments

The authors are grateful to their colleagues and students for their contributions to the development of this textbook. Although there are too many contributors to name, a few deserve special mention. Professor P. Aarne Vesilind was an inspiration for much of the content of this textbook. Professor Vesilind's devotion to the ethical uses of engineering skills to improve the human condition were foundational for many of his students, colleagues, and peers, and his lifelong works and words are influential in this edition of *Environmental Engineering and Sustainable Design.*

Dr. Striebig would like to thank two mentors, Dr. Raymond Regan and Dr. Robert J. Heinsohn, for encouragement throughout his career and with the development of this curriculum and textbook. He would like to acknowledge the support of his parents Janet and Ronald for making education a priority. Dr. Striebig is also indebted to his children, Echo and Zachary, who are a constant inspiration for the hope and potential of future generations.

Dr. Papadakis owes her love of technology to her father, Pete Papadakis, a career-long experimental stress and design engineer. Tom Walls, Robert Zetzl, Gladys Good, and Donald Clodfelter had a bigger impact than they could possibly know, and innately understood the needs of K-12 girls in STEM decades before this issue came to national prominence. She would like to thank her husband Fred Copithorn for his steady presence and love of the Earth, and her mother Iris Joseph continues to be a profound role model.

Dr. Heine was a graduate student of P. Aarne Vesilind and is profoundly grateful for his mentorship and love of teaching. Lauren is grateful to her parents Arthur and Sherry Glass for their support and for showing her how environmental engineering is integral to our daily lives. She would like to thank her husband Carl, and Hani and Cooper for their love and support; as well as dear friend and chemist Laura Gray for helping to ensure that the problems and active learning exercises are engaging and challenging. She would also like to thank Chem*FORWARD* friend and co-founder, Stacy Glass, for her vision and for valuing educational endeavors.

Dr. Ogundipe will be forever indebted to Dr. Washington Braida; a terrific teacher and friend who inspired him and pointed him in the right direction. He would also like to thank Tola, Safiyyah, Haneef, and Sumayyah for being the reason.

Last but certainly not least, the authors wish to thank the Global Engineering team at Cengage Learning for their dedication to this new edition: Timothy Anderson, Senior Product Manager; MariCarmen Constable, Learning Designer; Alexander Sham, Content Manager; and Simeon Lloyd-Wingard, Product Assistant. Thanks are also due to Rose P. Kernan of RPK Editorial Services.

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Professor Ogundipe's academic background is in Chemical and Environmental Engineering. His current areas of specialization and scholarship include Life Cycle Analysis, Industrial Ecology, and developing methods for assessing sustainability. His ongoing cross disciplinary work involves international collaborations aimed at developing appropriate educational modules to help engineering students develop global cultural competencies.

Digital Resources

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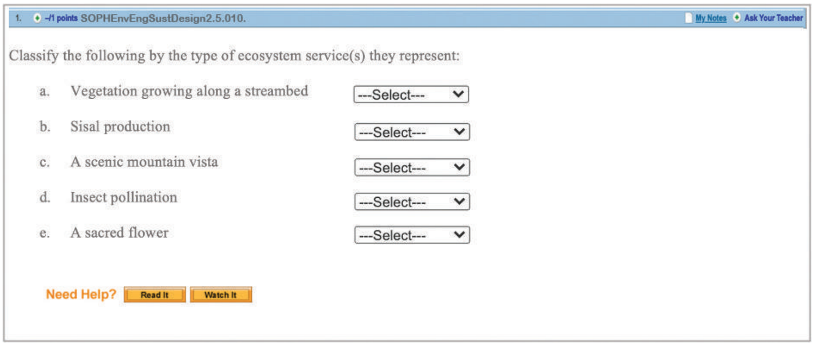

- **My Class Insights**
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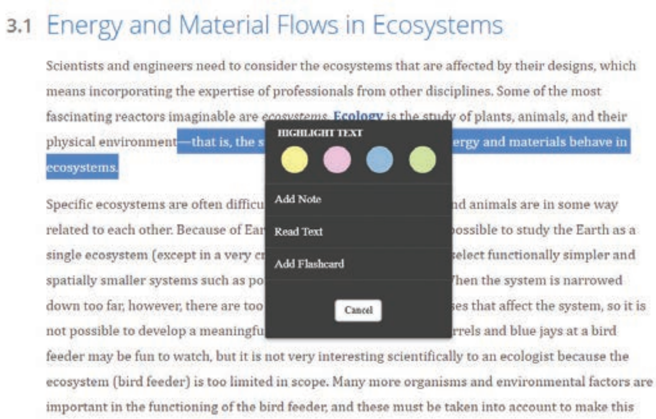

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PART 1

Environmental and Sustainability Science Principles

CONTENTS

CHAPTER 1

Sustainability, Engineering, and Design

FIGURE 1.1 A high-resolution photo of our planet showing various ecosystems and weather patterns. Many believe the first images of Earth taken from space had a profound effect on how people in general perceived the interconnectedness between people, the planet, and future prosperity.

Source: NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group. Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

It is known that there are an infinite number of worlds, simply because there is an infinite amount of space for them to be in. However, not every one of them is inhabited. Any finite number divided by infinity is as near nothing as makes no odds, so the average population of all the planets in the Universe can be said to be zero. From this it follows that the population of the whole Universe is also zero, and that any people you may meet from time to time are merely products of a deranged imagination.

—Douglas Adams, from *The Restaurant at the End of the Universe* (1980, p. 142)

GOALS

THE EDUCATIONAL GOALS OF THIS CHAPTER are to define sustainability and understand how social norms influence discussions about sustainability. We also examine how population changes and resource consumption have created the need for engineers, economists, scientists, and policymakers to consider sustainability in the design of products, infrastructure, and systems. The key concepts that are used to quantitatively consider sustainable design include the human development index, population growth models, and the ecological footprints analysis. This chapter also provides a greater context for the social and economic factors that shape successful design. In this chapter, we explore the ethical basis of human-centered design as a way of meeting the essential needs of people, which is an explicit element of sustainable development. In addition, we explain the dynamics of the adoption and diffusion of innovations, which is a critical prerequisite to the widespread social impact of more sustainable practices, products, and processes. Finally, we address the economic concepts that help us understand why achieving greater environmental sustainability can be a challenge and the role of governmental policymaking in surmounting those obstacles.

OBJECTIVES

At the conclusion of this chapter, you should be able to:

1.1 Calculate and relate the Human Development Index to indices for lifespan, education, and income.

1.2 Discuss ethical frameworks and engineering ethics in relation to sustainability.

1.3 Explain the different ethical principles that inform sustainable development, and discuss how these affect engineering design.

1.4 Give examples of successful and unsuccessful technologies appropriate for meeting the essential needs of people, and explain the reasons for their success or failure.

1.5 Define and discuss different definitions of sustainability, sustainable design, and sustainable development.

1.6 Evaluate global trends in population and describe how those trends challenge engineers to develop sustainable products, infrastructure, and systems.

1.7 Define and evaluate the carrying capacity of systems of various scales.

1.8 Define and discuss quantitatively the indicators of sustainable design, including the ecological footprint and the impact, population, affluence, and technology (IPAT) equation.

1.9 For a given innovation, summarize and analyze the social, cultural, technical, and economic factors that affect its potential impacts.

Introduction

Genetically modern humans appeared on Earth about 200,000 years ago, and biologically and behaviorally modern humans appeared about 70,000 years ago. The number of people and their effects on the planet were negligible for most of the history of the planet (Figure 1.2).

The number of humans on the planet remained very small until a few hundred years ago when advances in farming, energy, and mechanization took place, allowing the human population to increase exponentially (see Figure 1.3). Rapid changes in technology allowed humans to live longer; the decreasing death rates contributed to the high rate of human population growth over the past thousand years. Some time shortly after the year 1800, the world population reached 1 billion people for the first time (UN, 1999).

Demographers, people who study trends in population, say we are likely heading toward a world population of 9.5 to 12.5 billion over the next century (UN, 2019). While the human population on the planet is growing, natural resources that we have relied on for food, energy, and water are shrinking owing to the increasing human consumption of those resources. The human species has had a profound environmental impact on the planet, threatening the Earth's biodiversity, climate, energy resources, and water supply.

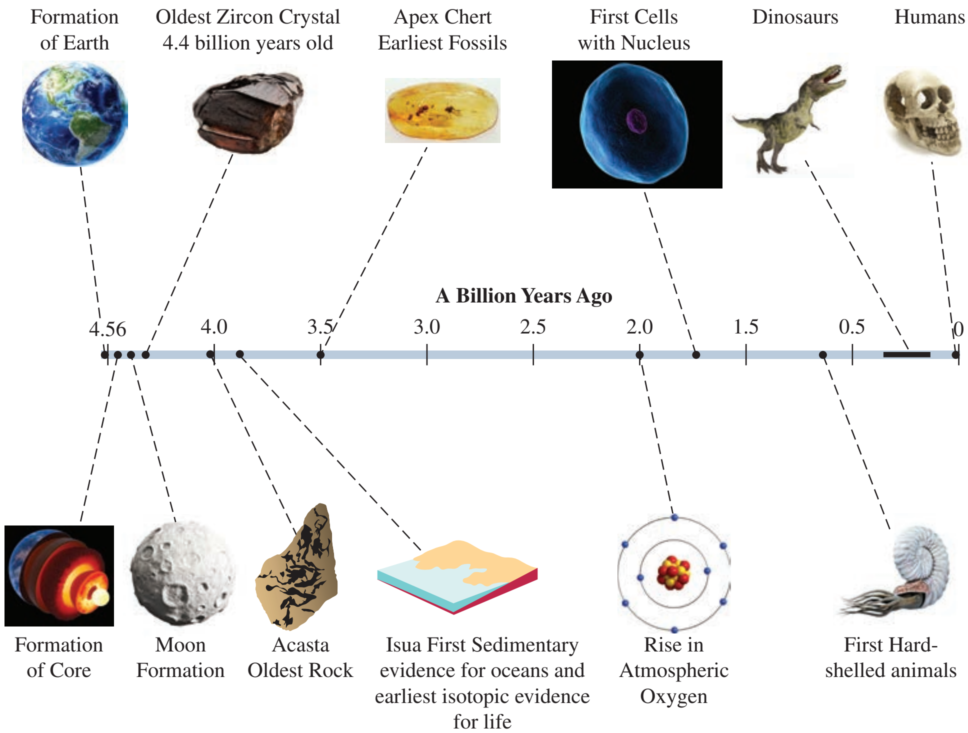


FIGURE 1.2 A timeline of planetary history showing the relatively short time humans have existed on Earth compared to the entirety of the history of Earth.

Source: Based on www.geology.wisc.edu/zircon/Earliest%20Piece/Images/28.jpg; leonello calvetti/Shutterstock.com; Johan Swanepoel/Shutterstock.com; Ortodox/Shutterstock.com; Imfoto/Shutterstock.com; falk/Shutterstock.com; oorka/Shutterstock.com; Sebastian Kaulitzki/Shutterstock.com; Number001/Shutterstock.com; DM7/Shutterstock.com; Empiric7/Shutterstock.com; SciePro/Shutterstock.com.

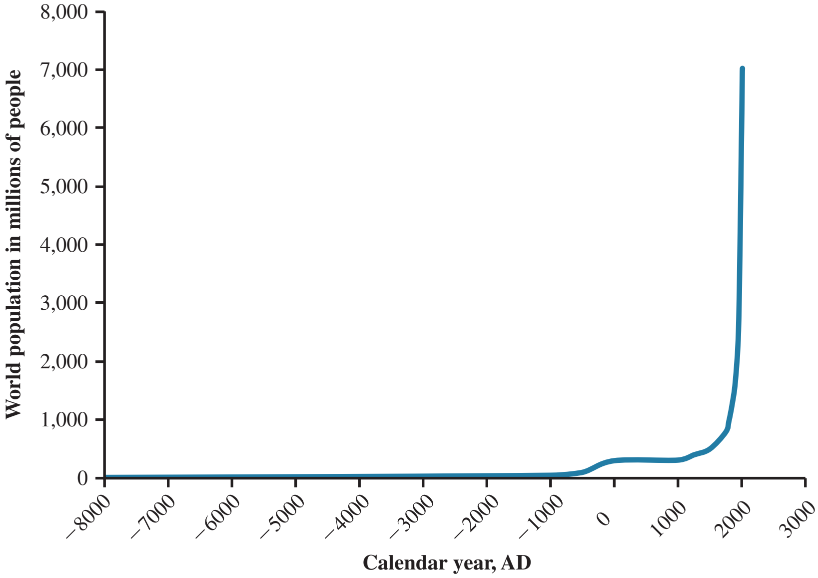


FIGURE 1.3 Historic estimates of human population from pre-history until 2011.

Source: Based on Kremer, M. (1993). "Population Growth and Technological Change: One Million B.C. to 1990." *The Quarterly Journal of Economics* 108(3): 681–716. AD 0–1990: United Nations Population Division Report, *The World at Six Billion. AD 1995–2012*: U.S. Census Bureau Data: *The World Population Clock*.

In the industrialized world, many people move faster, eat more, know more, and live in larger homes than even royalty could have dreamed of only a few centuries ago. Yet despite the great advances in science, technology, government, economics, education, and medicine over the past hundred years, these resources are not distributed equally on the planet. Economic, scientific, and technological advances have increased the lifespan and improved access to many marvelous things in the industrialized world, but this overall increase in the standard of living has failed to raise many people out of poverty. The standard of living relates income, comfort, and material goods to the socioeconomic classification of people. Scientists and engineers have played a key role in increasing both the average human life span and standard of living through applications of energy development and distribution, water treatment, sanitation, and other technological advances. As we will see later in this chapter, those who have not benefited from modern science, technology, and industrialization may not be able to meet their basic needs for food, clothing, shelter, water, and sanitation.

ACTIVE LEARNING EXERCISE 1.1 **Preconceptions about Sustainability**

Define "sustainability" in your own words to the best of your ability. Sketch a visualization of your definition using a cartoon or mind map. Show the linkages to things you perceive are related to sustainability on your sketch. Share your sketch with peers, and listen to how your peers think your sketch illustrates concepts of sustainability.

1.1 Human Development Index

The United Nations Development Programme (UNDP) devised a ***Human Development Index (HDI)*** that is based on three dimensions: life expectancy, education, and income. These dimensions are combined into a single comparable value, as illustrated in Figure 1.4 (UN, 2011a). The HDI is calculated using the data reported each year by the United Nations and the following equations (1.1) to (1.6.)

Life expectancy (LE) at birth uses the 2018 Life Expectancy Index:

$$\text{Life Expectancy Index (LEI)} = (\text{LE} - 20)/(85 - 20) \tag{1.1}$$

The Education Index (EI) is based on the Mean Years of Schooling Index (MYSI) and Expected Years of Schooling Index (EYSI), where

$$\text{MYSI} = \text{mean years of schooling}/15 \tag{1.2}$$

$$\text{EYSI} = \text{expected years of schooling}/18 \tag{1.3}$$

$$\text{EI} = (\text{MYSI} + \text{EYSI})/2 \tag{1.4}$$

The Income Index (II) is based on the gross national income (GNI_{pc}) at purchasing power parity (PPP) per capita, which is an estimate and standardization of each individual's income in a country:

$$\text{II} = \{\ln(\text{GNI}_{pc}) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\} \tag{1.5}$$

The Human Development Index is determined from the geometric mean of the Life Expectancy Index, the Education Index, and the Income Index:

$$\text{HDI} = (\text{LEI} \times \text{EI} \times \text{II})^{1/3} \tag{1.6}$$

Based on this index, the United Nations categorizes countries as Very High Human Development ($HDI \geq 0.800$), High Human Development ($0.800 > HDI \geq 0.700$), Medium Human Development ($0.700 > HDI \geq 0.550$), and Low Human Development ($HDI < 0.550$).

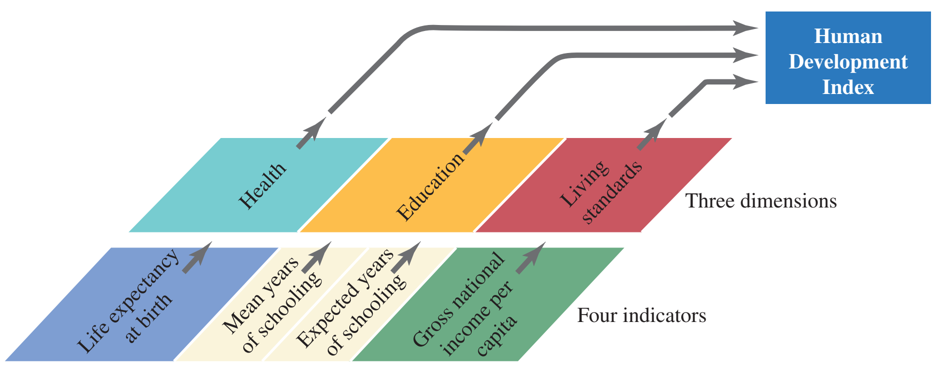


FIGURE 1.4 Components of the Human Development Index.

Source: Based on *Human Development Report 2011.* Sustainability and Equity: A Better Future for All. United Nations Development Programme.

EXAMPLE 1.1 Calculating the Human Development Index

Calculate the Human Development Index for the selected countries from 2018 data.

TABLE 1.1 Component values of the Human Development Index for selected countries

COUNTRY	LIFE EXPECTANCY AT BIRTH (YEARS)	EXPECTED YEARS OF SCHOOLING (YEARS)	MEAN YEARS OF SCHOOLING (YEARS)	GROSS NATIONAL INCOME (GNI) PER CAPITA (2011 PPI $)
Benin	60.2	12.6	3.6	2,061
Costa Rica	80.0	15.4	8.8	14,636
India	68.8	12.3	6.4	6,353
Jordan	74.5	13.1	10.4	8,288
Norway	82.3	17.9	12.6	68,012
United States	79.5	16.5	13.4	54,941

Source: Based on the *Human Development Report 2019*. Beyond income, beyond averages, beyond today: Inequalities in human development in the 21st century. New York. ISBN: 978-92-1-126439-5.

For Benin, the Life Expectancy Index can be calculated using Equation (1.1) from the life expectancy at birth:

$$(\text{LEI}) = (\text{LE} - 20)/(85 - 20)$$
$$= (60.2 - 20)/65$$
$$= 0.618$$

In order to calculate the Education Index, we first need to calculate the Mean Years of Schooling Index (MYSI) and the Expected Years of Schooling Index (EYSI) from Equations (1.2) and (1.3), respectively:

$$\text{MYSI} = \text{mean years of schooling}/15$$
$$= 12.6/15 = 0.840$$
$$\text{EYSI} = \text{expected years of schooling}/18$$
$$= 3.6/18 = 0.20$$

Substituting into the equation for the education index yields

$$\text{EI} = (\text{MYSI} + \text{EYSI})/2$$
$$= (0.840 + 0.20)/2 = 0.520$$

We can calculate the Income Index (II) from the gross national income (GNI_{pc}) at purchasing power parity per capita using Equation (1.5):

$$\text{II} = \{\ln(\text{GNI}_{pc}) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\}$$
$$= \{\ln(2{,}061) - \ln(100)\}/\{\ln(75{,}000) - \ln(100)\} = 0.457$$

We can then use the Life Expectancy Index, Education Index, and Income Index to calculate the HDI using Equation (1.6):

$$\text{HDI} = (\text{LEI} \times \text{EI} \times \text{II})^{1/3}$$

$$= (0.618 \times 0.520 \times 0.457)^{1/3} = 0.528$$

The HDI of 0.528 is much less than 1. Using the 2018 data from the United Nations for the countries given yields the HDI values for selected countries shown in Table 1.2.

TABLE 1.2 Calculated values for the subparts of the Human Development Index

COUNTRY	LEI	EI	II	HDI	2018 HDI RANKING OF COUNTRIES
Benin	0.618	0.520	0.457	0.528	163
Costa Rica	0.923	0.758	0.753	0.808	63
India	0.751	0.588	0.627	0.652	130
Jordan	0.838	0.726	0.667	0.740	95
Norway	0.958	0.947	0.985	0.963	1
United States	0.915	0.922	0.953	0.953	13

From Table 1.2, we can see significant gaps in resources associated with life expectancy, education, and income. Norway had the highest HDI score in 2018, followed by the United States. Both Norway and the United States are listed in the United Nations' Very High Human Development category. People living in Costa Rica and Jordan have a similar life expectancy as those living in the United States and Norway, but they would have lower education and income expectations. The United Nations classifies Jordan as a High Human Development nation. India has a lower life expectancy, educational index, and significantly lower income index, and is listed in the United Nations' Medium Human Development category. Benin has a much lower index score in each category than all the previous countries we mentioned, as is the case of many sub-Saharan African nations. This discrepancy in development is illustrated in Figure 1.5. Benin and other countries with little infrastructure, challenged educational systems, low life expectancy, and low expected income values are categorized as Low Human Development countries by the United Nations.

Figure 1.5 illustrates the uneven distribution and ranking of HDIs. By most definitions, in the year 2012, a total of 2.8 billion people lived in poverty or had income levels of less than 2 U.S. dollars per day. Nearly 1.4 billion lived in extreme poverty, earning less than 1.25 U.S. dollars per day (UN, 2012a). Over 850 million people were undernourished and lacked access to food. Approximately 2.5 billion people lacked access to either clean water or sanitation (UN, 2012a). These numbers illustrate the need for a large percentage of the world's population to improve their standard of living. Population numbers alone do not tell the whole story of resource consumption, the uneven distribution of scarce resources, and the desire of many people living in poverty to improve their access to food, water, energy, education, and economic development.

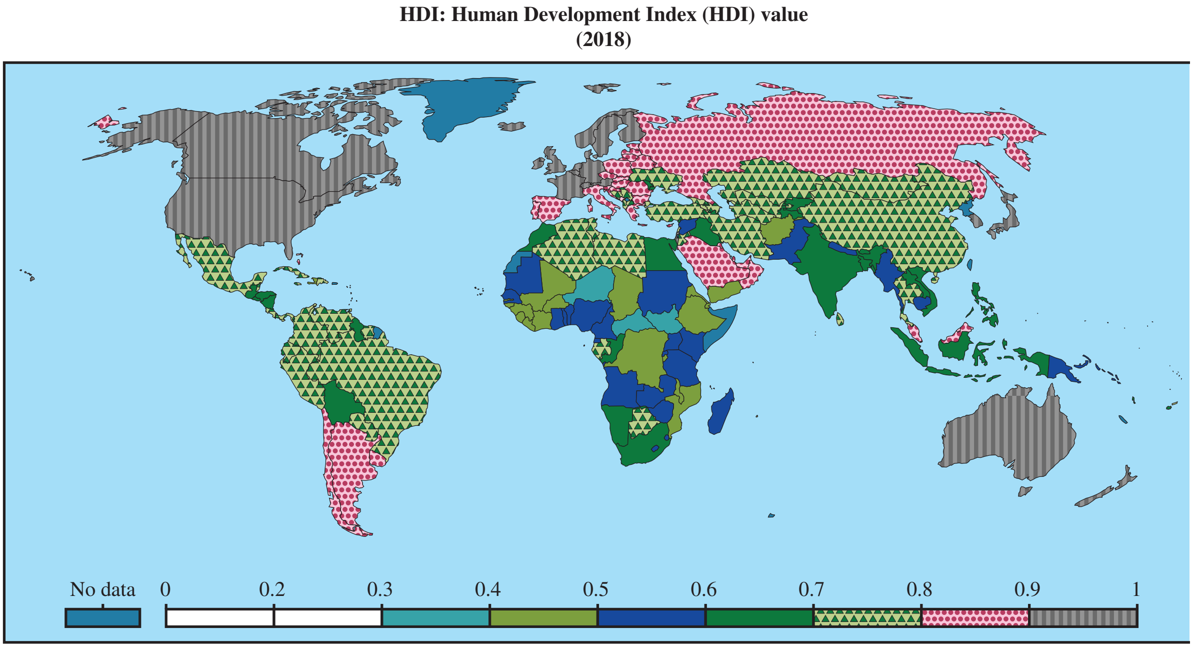


FIGURE 1.5 A map of country rankings based on the United Nations' Human Development Index.

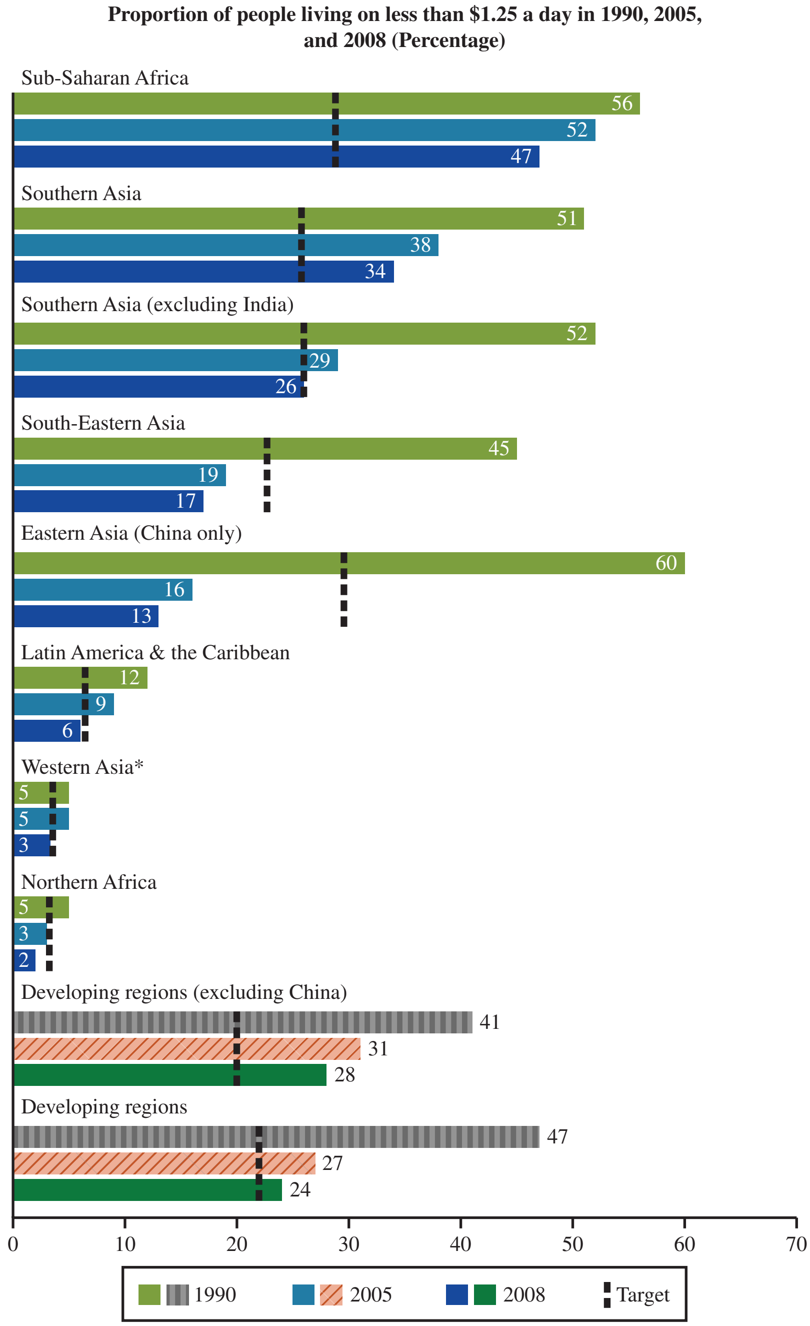
Source: Based on Roser, M. (2019). *"Human Development Index (HDI)."* Published online at OurWorldInData.org.

Mahbub ul Haq (1934–1998), the founder of the *Human Development Report*, said that the purpose of development is:

> *to enlarge people's choices. In principle, these choices can be infinite and can change over time. People often value achievements that do not show up at all, or not immediately, in income or growth figures: greater access to knowledge, better nutrition and health services, more secure livelihoods, security against crime and physical violence, satisfying leisure hours, political and cultural freedoms and sense of participation in community activities. The objective of development is to create an enabling environment for people to enjoy long, healthy and creative lives.*

Sustainable development in one sense is the desire to improve the worldwide standard of living while considering the effects of economic development on natural resources. Since 1990, significant strides have been taken to decrease the percentage of the world's population living in poverty (Figure 1.6). The most significant gains have come from the industrialization of large population centers in Asia.

As economic centers and industrial centers continue to develop and transform our landscape, more and more people are looking to these centers as a means to improve their standard of living. As a result, current trends show that populations are migrating toward more centralized cities and urban areas (Figure 1.7). This rural-to-urban migration places significant strain on the regions surrounding these cities and mega-cities (cities with more than 10 million people) (UN, 2008). Many countries that are becoming more industrialized are struggling to develop the infrastructure required to provide food, water, sanitation, and shelter for the rural migrants. Peri-urban areas are substantially increasing. ***Peri-urban areas***, characterized by very high population densities, lack the infrastructure to distribute energy, water, and sanitation services. These areas severely strain natural resources, especially water and energy.



* The aggregate value is based on 5 of 13 countries in the region.

Note: No sufficient country data are available to calculate the aggregate values for Oceania.

FIGURE 1.6 Since 1990, there has been a significant decrease in the number of people living in economic poverty, defined as subsistence on less than one dollar per day.

Source: Based on *The Millennium Development Goals Report 2012*. United Nations.

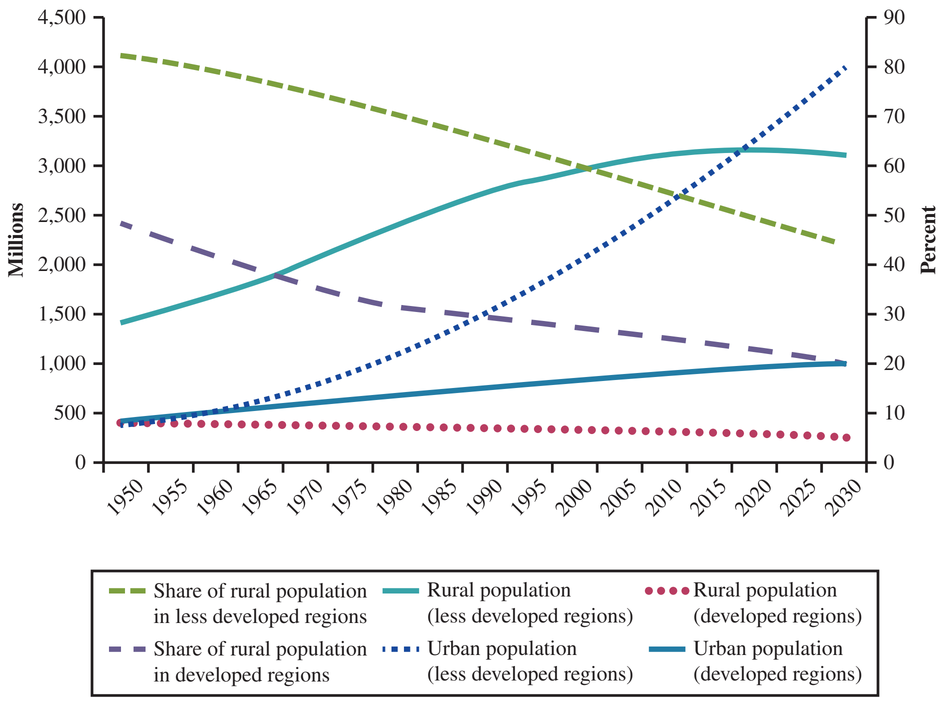


FIGURE 1.7 Trends in population migration into urban areas compared to decreasing population trends in rural areas for developed and less developed countries.

Source: Based on UN (2008). *Trends in Sustainable Development: Agriculture, rural development, land desertification and drought*. United Nations Department of Economic and Social Affairs Division for Sustainable Development.

1.2 Sustainable Development and Social Ethics

In many ways, the narrative that informs our contemporary understanding of sustainable development began over 50 years ago. Scientists, environmentalists, and economists identified a number of environmental and economic challenges associated with the unprecedented increase in global population growth and overconsumption described in the previous section. Connecting these threads, the United Nations requested that the World Commission on Environment and Development formulate "a global agenda for change." The commission articulated the concept of sustainable development in its holistic report *Our Common Future* (WCED, 1987 p. 41):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: (1) the concept of "needs," in particular the essential needs of the world's poor, to which overriding priority should be given; (2) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*

This definition of sustainable development is often referred to as the ***Brundtland definition***, named after the chairperson of the UN commission that produced the report. Importantly, the report and the definition of sustainable development linked the three key tenets (known as the three pillars) of sustainability: the environment, society, and the economy. Although the report was published over a quarter of a century ago, it still serves as an important reference point for discussion of the definition, motivation, and challenges associated with sustainable development.

There are implicit ethical dimensions of the definition of sustainable development that generally build on the concepts of equity, fairness, and justice. It is important for an engineer or designer to be able to identify these ethical dimensions of sustainability, as they often directly inform the policies and regulations that influence engineering design decisions.

In the context of the Brundtland definition, intergenerational equity refers to the use of natural resources in such a way as to take into consideration the needs of both the present and future generations. The UN Rio Declaration in 1992 defined ***intergenerational equity*** more broadly, stating that "the right to development must be fulfilled so as to equitably meet developmental and environmental needs for both present and future generations." Intergenerational equity, then, is the ethical obligation of current societies to consider the welfare of future societies in the context of natural resource use and degradation (Makuch and Pereira, 2012). Engineers play a critical role in facilitating intergenerational equity, as we design systems, processes, and products that can ensure that natural resources will be conserved in such a way that future generations can use them.

Sustainable development also includes the notion of intragenerational equity, that is, the need for equity within members of the same generation. Intragenerational equity is often referenced in instances of economic inequity, for example, between developed and developing countries. In the Brundtland definition, it provides the motivation for prioritizing the needs of people with less means. In international treaties such as the Kyoto Protocol, intragenerational equity is the principle used to define common but differing responsibilities between countries at various stages of economic development. In the context of the Kyoto Protocol, developed and developing countries do not have identical obligations to mitigate

BOX 1.1 Formative Works Related to Sustainable Development

In 1956 a geoscientist who worked at Shell research lab named Dr. M. King Hubbert suggested that oil production in the United States would peak and followed a bell-shaped curve (Hubbert and American Petroleum, 1956). His work became a cornerstone of the notion of peak oil (i.e., the point in time where the rate of total petroleum extraction begins to decline permanently) and underlined the point that oil is a finite and depleting resource used as a fuel for economic development.

A few years later (Figure 1.8), the marine biologist Rachel Carson published *Silent Spring* (1962), which chronicled the negative impacts associated with pesticides and facilitated the ban of the pesticide DDT a decade later. This book is often cited as helping to begin the environmental movement in America.

In "The Tragedy of the Commons" (1968), ecologist Dr. Garret Hardin explored some of the moral and social challenges related to population growth and the management and use of natural resources.

The Limits to Growth (1972), by Donella Meadows, Dennis Meadows, Jørgen Randers, and William W. Behrens III, provided the first effort to holistically model the global system with respect to five key indicators of sustainability: world population, industrialization, pollution, food production, and resource depletion.

In *Small Is Beautiful* (1973), E. F. Schumacher critiqued modern economists, for example, for their treatment of natural resources such as oil as non-depleting. His work has since been applied to engineering design through appropriate technology.

- 1949 • Aldo Leopold publishes *A Sand County Almanac*
- 1952 • Dr. Albert Schweitzer receives the Nobel Peace Prize for his writings about the "Reverence of Life"
- 1956 • Dr. M. King Hubbert recognizes the limitations of known oil reserves
- 1962 • Rachel Carson publishes *Silent Spring*
- 1968 • Dr. Garret Hardin writes "The Tragedy of the Commons"
- 1972 • *The Limits of Growth* is published
- 1973 • E. F. Schumacher publishes *Small Is Beautiful*
- 1973 • Arne Naess coins the term *deep ecology* and describes its philosophical foundation
- 1986 • Paul Taylor publishes *Respect for Nature: A Theory of Environmental Ethics*
- 1987 • *Our Common Future* is published by the United Nations
- 1992 • United Nations Conference on Environment and Development is held and results in the promotion of Agenda 21, which is a nonbinding voluntary action to promote sustainable development
- 2000 • United Nations promotes eight Millennium Development Goals

FIGURE 1.8 Formative works in developing the current philosophical underpinnings that support sustainable development.

climate change. Rather, their requirements for action under the treaty are equitably scaled to reflect differences in their economic and infrastructure capacities (Makuch and Pereira, 2012). ***Social justice*** is similar to intragenerational equity, but it is concerned more specifically with the fair distribution (or sharing) of the advantages and disadvantages (or benefits and burdens) that exist within society.

Given the evolution of the concept of sustainable development, it is not surprising that arguments for sustainability hinge upon the concept of social justice. In the context of sustainable development, environmental justice deals with the fair distribution of environmental benefits and burdens. The lines between environmental and social justice are occasionally blurred. However, because their objectives may at times differ, it is useful to keep them distinct.

1.3 Sustainable International Development and the Essential Needs of People

The Brundtland definition of sustainable development includes a focus on meeting the essential needs of people, such as basic human needs for food, water, and shelter. However, essential needs also include opportunities for the educational advantages and economic productivity that improve quality of life.

Developing communities often face a systemic lack of access to services that would meet their basic needs. For example, over 2 billion people worldwide lack access to improved sources of drinking water, and 3.6 billion lack access to improved sanitation, with significant disparity within and between countries (UNICEF and WHO, 2021). With respect to energy use and access, 759 million people lack access to electricity, and 2.6 billion people need clean cooking facilities (IEA, 2021). Significant disparities also exist. For example, 95% of those without access are in sub-Saharan Africa or developing Asia, and 84% live in rural areas (IEA, 2011).

This lack of access results in negative impacts on both health and economic development. For example, indoor air pollution from the use of traditional fuels such as charcoal and wood for household energy contributes to 3.8 million deaths per year (IEA, 2021). Gathering fuel wood and water also reduces the time available for education and economic activity—a burden disproportionately shared by women and children (Figure 1.9).

As more people use more water and produce more waste products that contaminate potential water supplies, engineers, scientists, and policymakers have tried to create a model for development that balances all these considerations. World leaders have focused on the relationship between development, population growth, and

FIGURE 1.9 Gathering fuel wood and water in Benin, West Africa. The physical labor of gathering fuel wood for cooking and collecting water is often the work of women and children in low-income countries. This represents a high social cost, as it takes them away from opportunities for schooling or engaging in business endeavors.

Source: Bradley Striebig.

natural resource management for many years. One of the most profound statements about these interrelationships is the United Nations Agenda 21 from the ***Conference on Environment and Development***, held in Rio de Janeiro, Brazil, in 1992:

> *Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being.*

The statement continues:

> *Human beings are at the center of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature. The right to development must . . . meet developmental and environmental needs of present and future generations. All States and all people shall cooperate in the essential task of eradicating poverty as an indispensable requirement for sustainable development. . . . To achieve sustainable development and a higher quality of life for all people, States should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies.*

In the year 2000, the United Nations specified eight ***Millennium Development Goals*** to address prior to 2015. Overall the Millennium Development Goals have potentially saved over 21 million extra lives due to accelerated progress, as illustrated in Figure 1.10. “The MDGs helped to lift more than one billion people out of extreme poverty, to make inroads against hunger, to enable more girls to attend school than ever before and to protect our planet,” the UN Secretary General Ban Ki-moon explained. But he did not finish there. “Yet for all the remarkable gains, I am keenly aware that inequalities persist and that progress has been uneven.” The progress on each individual goal and target varied and results also varied across different geographic regions, as shown in Figure 1.11.

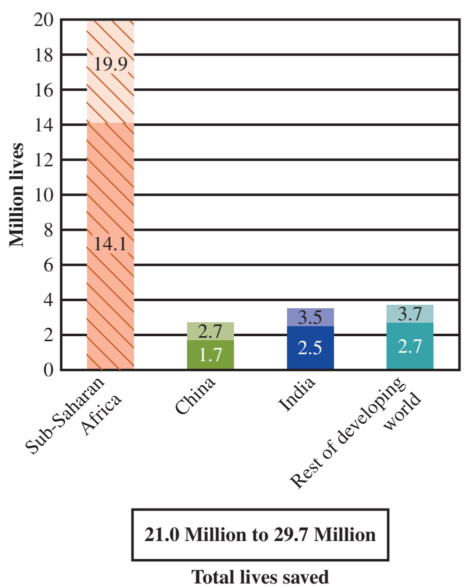


FIGURE 1.10 Indicators that the UN Millennium Development Goals successfully reduced mortality.

Source: Data from www.brookings.edu/blog/future-development/2017/01/11/how-successful-were-the-millennium-development-goals/.

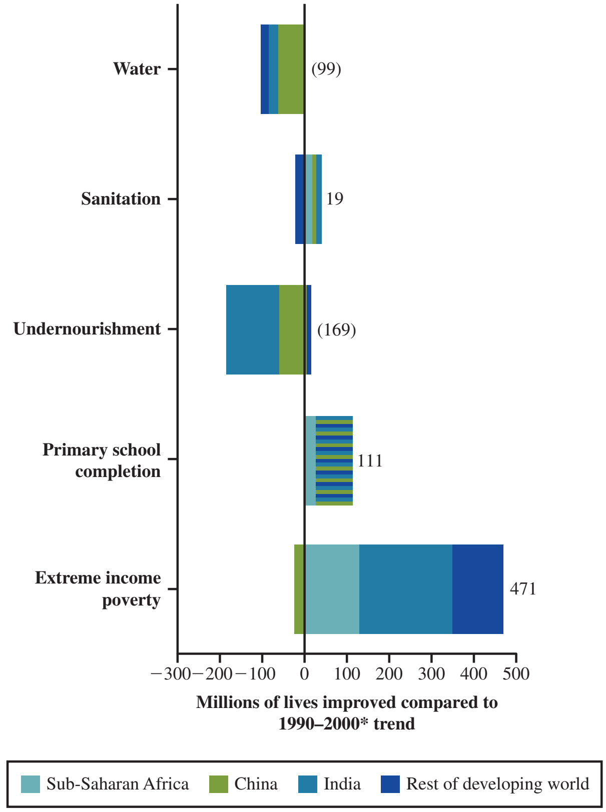


FIGURE 1.11 Indicators that the UN Millennium Development Goals had mixed results compared to trends in the prior decade. It should be noted that overall progress was still important; for example, MGD targets for access to water were met by 2010 and focus may have appropriately shifted toward sanitation issues.

Source: Data from www.brookings.edu/blog/future-development/2017/01/11/how-successful-were-the-millennium-development-goals/.

The Millennium Development Goals from the year 2000 were:

1. **Eradicate extreme poverty and hunger:** The target of reducing extreme poverty rates—people living on just $1.25 a day—by half was met five years ahead of the 2015 deadline. Globally the number of people living in extreme poverty fell from 1.9 billion in 1990 to 836 million in 2015. The second target of halving the proportion of people suffering from hunger was narrowly missed. The proportion of undernourished people in developing regions fell from 23.3% in 1990 to 12.9% in 2014.
2. **Achieve universal primary education:** Primary school enrollment figures rose substantially, as the primary school enrollment rate in developing regions reached 91% in 2015, up from 83% in 2000.
3. **Promote gender equality and empower women:** About two-thirds of developing countries achieved gender parity in primary education. Only 74 girls were enrolled in primary school for every 100 boys in 1990. Today, 103 girls are enrolled for every 100 boys.
4. **Reduce childhood mortality:** The global under-5 mortality rate declined by more than half since 1990—dropping from 90 to 43 deaths per 1,000 live births. This falls short of the targeted drop of two-thirds. In practical terms, this means 16,000 children under 5 continue to die every day from preventable causes.

5. **Improve maternal health:** Since 1990, the maternal mortality rate has been cut nearly in half, albeit falling short of the two-thirds reduction goal. There were an estimated 289,000 maternal deaths in 2013.
6. **Combat HIV/AIDS, malaria, and other diseases:** Although the number of new HIV infections fell by 40% between 2000 and 2013, the target of halting and beginning to reverse the spread of HIV/AIDS has not been met. According to the UN, over 6.2 million malaria deaths were averted between 2000 and 2015, primarily those of children under 5 years old in sub-Saharan Africa. The global malaria incidence rate fell by an estimated 37% and the mortality rate by 58%.
7. **Ensure environmental sustainability:** The target of halving the proportion of people without access to safe water was achieved. Between 1990 and 2015, 2.6 billion people gained access to improved drinking water. However, 663 million people across the world still do not have access to improved drinking water, and proper sanitation remains a challenge for low development areas of the world.
8. **Develop a global partnership for development:** Official development assistance from wealthy countries to developing countries increased by 66% between 2000 and 2014.

The Millennium Development Goals ended in 2015, after successfully achieving many of the desired goals in some parts of the planet. The MDG's successor—the 17 Sustainable Development Goals (SDGs) shown in Figure 1.12—were adopted by world leaders at a summit in New York in September 2015. Countries are tasked to mobilize efforts to end all forms of poverty, fight inequalities, and tackle climate change, while ensuring that no one is left behind.

FIGURE 1.12 The 17 United Nations Sustainable Development Goals.

Source: MintBlak/Shutterstock.com.

The SDGs build on the success of the Millennium Development Goals and aim to go further to end all forms of poverty. The new goals are unique in that they call for action by all countries to promote prosperity while protecting the planet. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs, including education, health, social protection, and job opportunities, while also tackling climate change and environmental protection.

How can sustainable development be achieved if there are more people using more resources? In order to answer this complex question, we must first examine the definition of sustainability and understand the context associated with the term. The term *sustainable* or *sustainability* is widely used in a variety of applications, contexts, and marketing materials. Most of the uses of the word "sustainable" infer a qualitative comparison to something "other"; for example, "*our new green Excellon automobile is the sustainable solution to yesterday's sports utility vehicle (SUV).*" There is little or no quantifiable way to compare and contrast the advantages and disadvantages of the two products. Nor is there an attempt to explain how a product can be sustainably produced, sold, and disposed of for any significant period of time. The marketing of "sustainable" goods and products also typically infers that the "sustainable" product is morally superior to the less sustainable product.

Do you believe that sustainable products are morally superior to less sustainable products? If so, what does this belief imply about the developed world's largely consumer-based economic system of retail merchandise? How are technology and moral convictions woven into the fabric of our definitions of sustainable design?

The importance of defining quantitative measures of sustainability for design will be addressed in this chapter and throughout subsequent chapters. In order to determine if a product or process is sustainable, we must examine the consumption of raw materials, design life, cost, and ultimate disposal of a product. The context in which the product and process are developed should also be considered together with the societal implications of worldwide population growth and consumption patterns as well as with an evaluation of how an individual's environmental footprint may be affected by the product or process.

1.4 Engineering and Developing Communities

Engineers and designers play a key role in developing solutions for meeting the essential needs of people. However, to do this well, we must pay attention to the technical, cultural, economic, and environmental contexts that can affect project outcomes. Countless engineering and design efforts in developing communities have failed to meet expectations for sustained (and positive) societal impact. For example, in sub -Saharan Africa, 35% of rural water systems are nonfunctioning, with some countries experiencing an operational failure rate of 30% to 60% (Harvey and Reed, 2007). These high failure rates generally do not occur because of technical design flaws, but because of the failure to incorporate other salient factors through the design process, including social, economic, and environmental influences. Point-of-use (POU) water treatment technologies, like those described in Table 1.3, may be better suited to significantly reduce the risk of exposure to pathogenic organisms in drinking water.

Engineers and designers are now better equipped to incorporate these key social, economic, and environmental factors into their design and implementation decisions than they were several decades ago. Generally, two dimensions of design require a shift in thinking for sustainable engineering in developing countries. The first dimension involves a shift in thinking with regard to *product*, and the second, with regard to *process*.

TABLE 1.3 Point-of-use (POU) appropriate water treatment technologies considered for implementation in the model home near Kigali, Rwanda

TECHNOLOGY	DESCRIPTION	ADVANTAGE	DISADVANTAGE	REFERENCES
Biosand™	Sand filtration	• High removal efficiency for microorganisms	• Needs continual use and regular maintenance • Cost	Duke et al. (2006); Stauber et al. (2006)
Filtron™	Ceramic filter	• High removal efficiency for microorganisms • Sized for individual homes • Relatively inexpensive	• Requires fuel for construction • Limited lifetime • Requires regular cleaning	Bielefeldt et al. (2010); Brown and Sobsey (2010); Clasen et al. (2004); Striebig et al. (2007); van Halem et al. (2009)
SODIS™	Solar water disinfection	• Highly effective • Inexpensive • Can reuse a waste product (PET bottles)	• Long treatment time (6 to 48 hours) • Does not remove other potential pollutants • Requires warm climate and sunlight	Conroy et al. (2001); Kehoe et al. (2001); Mania et al. (2006); Meierhofer and Wegelin (2002); Sommer et al. (1997)

Source: Based on Striebig, B., Atwood, S., Johnson, B., Lemkau, B., Shamrell, J., Spuler, P., Stanek, K., Vernon, A., and Young., J. (2007). "Activated carbon amended ceramic drinking water filters for Benin." *Journal of Engineering for Sustainable Development* 2(1):1–12.

In terms of products, engineers and designers have transitioned to the concept of ***appropriate technology***. While this term has many differing meanings, it is used here to refer generally to engineering design that takes into consideration the key local social, economic, environmental, and technical factors that influence the success or failure of a design solution. That is, a technology (or design) is appropriate "when it is compatible with local, cultural, and economic conditions (i.e., the human, material and cultural resources of the economy), and utilizes locally available materials and energy resources, with tools and processes maintained and operationally controlled by the local population" (Conteh, 2003, p. 3). Appropriate technologies commonly considered when building homes or community buildings are briefly described in Table 1.4.

What does appropriate technology look like in practice? Consider, for example, the design of a point-of-use water supply and purification system for a rural household. In a high-income country, engineers would likely base their design decision on the amount of water needed by the household, size the system components for filtration, disinfection, and pumping accordingly, and then balance component quality and selection against the budgetary constraints of the household. In the case of a low-income country, engineers must still make these technical design decisions about system size and affordability, but they must also consider:

- Are parts readily available, either locally or nationally, if a component were to fail?
- Are there individuals who have the necessary skill or technical training to repair the component or system if it were to fail?
- Would members of the household readily understand how to use this system?
- What is the local availability of required infrastructures, such as electric power?

There is a significant body of literature on how to develop and design appropriate technology solutions for developing communities. These solutions tend to be

TABLE 1.4 Applications and uses of appropriate technology for medium- and low-income indexed countries

APPLICATION	TECHNOLOGY
Building design	Right-sized homes that maximize storage, comfort, social interactions, and use while minimizing the use of materials and energy. Natural ventilation can be integrated into a design by incorporating porches, central courtyards, other outside features, and strategically placed windows. Passive solar design maximizes exposure to the sun and takes advantage of the natural energy characteristics of building materials and air that are exposed to the energy of the sun. Overhangs take advantage of the thermal properties of the sun during the winter months while minimizing the sun's impact during the warmer summer months.
Power generation	Biogas power generation or microbial fuel cell technology can be integrated with waste management. Simple wind turbines may be made out of containers that would otherwise be disposed of as solid waste.
Material use in building construction	Appropriate, local, nontoxic, and reusable materials such as lime-stabilized rammed earth blocks, adobe, and straw bales can be promoted for building construction.
Stormwater management	Green roofs built on top of residential, commercial, and industrial structures not only effectively manage stormwater but also have benefits of reducing a building's energy consumption and regional urban heat island effect.
Water supply	Rainwater harvesting can assist groundwater recharge and provide all or a portion of domestic, commercial, and agricultural needs. It can also be incorporated into a building's cooling system.
Water treatment	*Moringa oleifera* tree seeds can be used to reduce turbidity. Other point-of-use treatment technologies described in Table 1.3 may be useful, especially in areas where power interruptions are frequent and those power interruptions frequently result in contamination of centralized piped drinking water supplies.

Source: Based on Hazeltine, B., and Bull, C. (2003). *Field Guide to Appropriate Technology*.

low-cost, culturally sensitive, and community-focused. They are also usually made and sourced from local supply chains. An added benefit of appropriate technology is that it can often be used as a tool for building human resource capacities in key areas, such as in electrical and mechanical skills and training. A wealth of information is now available on emerging appropriate technologies and addresses a wide range of essential human needs—for water, sanitation, energy, shelter, and so on—in developing communities. Global knowledge sharing about appropriate technology has greatly increased with the development of several online communities, such as *Engineering for Change* and *Appropedia* (Box 1.2).

Sustainable engineering focuses on both the design process itself and the implementation plan, and both are equally important to the technical design. The sustainable design process involves working with local community members to co-define the problem and its possible solutions, as well as to develop sound implementation plans. Community involvement is a hallmark of successful engineering design projects (Figure 1.13). It is through this process that appropriate technology can be used as a means of capacity building. In Bangladesh, an effort to provide solar energy and household lighting resulted in microlending opportunities that built local banking and financing capabilities (Box 1.3).

BOX 1.2 Online Resources for Appropriate Technology Solutions

Working on engineering solutions to meet the challenges in a developing community? Here are great resources to begin your exploration of possible strategies and ideas.

Engineering for Change (E4C): Founded by the American Society of Mechanical Engineers (ASME), Institute of Electrical and Electronics Engineers (IEEE), and Engineers Without Borders—USA (EWB-USA), E4C is a community of engineers, technologists, social scientists, non-governmental organizations (NGOs), local governments, and community advocates who work to develop locally appropriate and sustainable solutions for pressing humanitarian challenges. They maintain a "Solutions Library," which is a catalogue of appropriate technology solutions and case studies.

Website: www.engineeringforchange.org

Appropedia: This is a wiki that enables users to catalogue and collaborate on sustainability, appropriate technology, and poverty-reduction solutions. As with all crowd-sourced and community-managed wikis, the information on the site is best used for idea generation, as technical details are generally not independently validated.

Website: www.appropedia.org

Solar Cookers World Network: Another wiki-based site, the Solar Cookers World Network enables knowledge sharing on the design and construction of solar cookers.

Website: www.solarcooking.org

FIGURE 1.13 A Kenyan *Jiko*. This Kenyan cookstove is made of ceramic and tin and is an improved design that conserves scarce and costly charcoal and wood fuel. The final design resulted from collaboration between those who use them and the Massachusetts Institute of Technology engineers working on the project.

Source: Bradley Striebig.

BOX 1.3 Grameen Shakti (*Grameen Energy*)

Founded in 1996, Grameen Shakti is one of the world's largest suppliers of solar technologies, having installed nearly 100,000 solar photovoltaic systems in homes at a current rate of approximately 3,500 per month. Grameen Shakti is part of the Grameen Bank family, a microfinance enterprise for which its founder, Muhammad Yunus, won the Nobel Peace Prize.

Microfinance goes by several names, including microcredit and microlending. It operates by making extremely small loans to the poor without collateral or contract, and it relies on community peer pressure to assure loan repayment. Loans are given to individuals as investments that will allow borrowers an opportunity to surmount their poverty. An example is lending a woman money to purchase a sewing machine with which she can become a seamstress and earn an income. Indeed, the vast majority of Grameen microcredit is given to women.

With respect to Grameen Shakti, customers purchase their energy systems from the organization on a payment plan, usually a monthly installment over two or three years. Staff visit monthly to collect fees and perform maintenance on the systems. A typical photovoltaic system is used to power four light bulbs for four hours at night, enabling children to study and do their homework. Grameen Shakti also works with other renewable energy technologies, such as biogas applications and cook stoves.

Grameen Shakti is a unique social business in that it offers a complete package of technology integration: financing options to purchase the system, operational support of the technology, maintenance if the system breaks down, and technical advice on how to convert the product into a money-making tool. It is also unique in that it is location specific, providing remote, rural areas of Bangladesh with access to renewable energy technologies. This allows Grameen Shakti to make the design of the social aspects of its business sensitive to sociocultural factors that contribute to its success.

EXAMPLE 1.2 EWB House in Rwanda

Rwanda is a small country that lies in the heart of Central Africa. The capital of Rwanda is Kigali, a city that has grown very rapidly after the civil unrest that racked the country in the mid-1990s. As of 2002, Kigali City had 131,106 households, a total population of 604,966 (approximately 56% of which is age 20 years or under), and an annual growth rate of 10% (i.e., population will double every seven years) (Rwanda Ministry of Infrastructure, 2006).

The average Rwandan citizen consumed only 15.2 liters of water per day in 2002. The water cost was about a nickel (U.S.) each day. This may not sound like much, but that cost was more than 10% of the average daily wage! Water supply is still limited in Rwanda. Children are usually responsible for collecting the water. In Kimisange, a peri-urban area surrounding Kigali, the children carry the water over 0.25 kilometers from the nearest public water source, called a tapstand. However, this tapstand often runs dry, forcing the children to collect standing surface water in locations such as the one shown in Figure 1.14. The children may carry the water nearly 2 kilometers uphill back to their homes. Cooking fuel is also in short supply in Rwanda due to deforestation. Cooking fires with poor fuel continue to result in 10 to 11 deaths each day in many low-development countries such as Rwanda. Sewage in Rwanda is often discharged directly into the streets, which can contaminate the local water supply. The lack of access to clean

FIGURE 1.14 Photo showing typical housing, agriculture, and water sources in the peri-urban area near Kigali, Rwanda.

Source: Bradley Striebig.

water, energy, and sanitation has had a profound negative effect on human health. The average life expectancy in Rwanda in 2002 was only 47.3 years. The infant mortality rate was 89.61 infant deaths per 1,000 live births (WHO/UNICEF, 2005). Waterborne disease is suspected in killing one out of every five children born before the age of 5.

In 2004, an international group consisting of architects, engineers, and scientists led a project to demonstrate a low-income model home with sustainable on-site water, sanitation, and renewable sources of cooking fuel and fertilizer.

The local population of Kigali does not have the financial resources to invest in sanitation systems because they suffer from extreme poverty. Traditional centralized collection and treatment systems in the United States cost the average consumer 0.62 U.S. dollars per day (CIA, 2007). This would be nearly an entire day's wages or more for most people living in Kigali, so it is not a practical solution for Rwanda or most of the developing world. Existing centralized treatment facilities are expensive and require large amounts of energy for treatment and pumping. Ultimately, the traditional approach would not yield economically or environmentally sustainable solutions for sanitation or resource recovery in Kigali. Decentralized technologies are subject to failure due to poor maintenance and the costly disposal of residual wastes.

A group from Engineers Without Borders—USA and the Kigali Institute of Science and Technology worked with a community in Kigali to develop and optimize a scalable low-cost sustainable home. The home is made from reinforced low-cost bamboo and lime-stabilized earthen blocks, as shown in Figures 1.15 and 1.16. These blocks were produced at the site of the model home and will provide good insulation, keeping the interior warm during cool evenings and cool during warm days in Rwanda's very mild climate. Recovery of biogas will be used for cooking fuel and will help reduce deforestation due to the need to harvest wood for cooking. Rainwater will

FIGURE 1.15 Interlocked earth-block construction methods use inexpensive soil-based construction blocks that are made primarily from materials available near the construction site and use locally harvested bamboo reinforcement for construction.

Source: Photo used by permission of Chris Rollins.

FIGURE 1.16 Completed model home in Rwanda made from earth-block construction with a rainwater harvesting system shown in the foreground that is sitting on top of the visible portion of an underground biogas digester.

Source: Photo used by permission of Chris Rollins.

be collected from rooftops. This water can be used for drinking water, cooking, and sanitation. Drinking water is treated in model homes using a point-of-use treatment technology. Three treatment technologies (shown in Table 1.3) were considered for drinking water purification.

Construction and implementation of the model home occurred in 2007. Community-focused projects, such as this one, directly address eight of the Sustainable Development Goals set by the United Nations.

Sustainable Development Goals 1 and 2: No Poverty and Zero Hunger

Problems of poverty are inextricably linked to the availability and quality of water. Improving access to sanitation and the quality of water in the watershed can make a major contribution to eradicating poverty. Reliable shelter and biogas cooking fuel has the potential to reduce poverty and hunger.

Sustainable Development Goal 3: Good Health and Well-being
Sustainable Development Goal 4: Quality Education

Implementing safe sanitation practices and improving the water quality may reduce absenteeism and help students concentrate more fully on their education. Students and staff may benefit from the significant reduction in illness and absence from school due to the reduced exposure to pathogenic organisms. Furthermore, less time may be spent finding fuel for cooking since wood can be replaced by biogas.

Sustainable Development Goal 6: Clean Water and Sanitation

Increasing access to water can decrease the amount of time spent by young women retrieving water for use in the home, thereby increasing the likelihood those young women will do well in school and stay in school. Millions of children under the age of 5 die each year from preventable water-related diseases. The UN *Water World Development Report* states that, of all the people who died of diarrhea infections in 2001, 70% (or 1.4 million) were children. People weakened by HIV/AIDS are likely to suffer the most from the lack of a safe water supply and sanitation, especially from diarrhea and skin diseases. Access to pathogen-free drinking water may reduce childhood mortality and also reduce the suffering of people weakened by HIV/AIDS.

Waterborne diseases spread pathogens by the ingestion of urine- or feces-contaminated water. Typhoid fever, amoebic dysentery, schistosomiasis, and cholera are just a few of the diseases spread by contaminated water. Maternal mortality rates were estimated by the World Health Organization (WHO) to be 1 maternal death per 10 births. It is estimated that 203 of every 1,000 children die before the age of 5 in Rwanda. The model-building design increases access to water for drinking and hand washing. Promoting proper sanitation and providing the technology to implement point-source water treatment in the community will likely decrease childhood and maternal mortality rates in Kigali, Rwanda.

Sustainable Development Goal 11: Sustainable Cities and Communities

The earth-block model home addressed many of the indicators of sustainable development by meeting the current needs for wastewater treatment in the urban fringe of Kigali while conserving resources for future generations. The strategy reduced the spread of waterborne disease, while effectively treating wastewater so as not to exceed the assimilative capacity of native wetlands and also reduce the dependency on imported materials such as concrete and cement.

Sustainable Development Goal 17: Partnerships for the Goals

This project involved partnerships with the following organizations: the German Development Corporation (DED), Gonzaga University, Engineers Without Borders—USA, Tetra-Tech, Inc., the city of Kigali, the Kigali Institute for Science and Technology, and the National University of Rwanda.

ACTIVE LEARNING EXERCISE 1.2 Expectations about Common Resources

The next time you drink from a water fountain or buy a bottle of water, what are your expectations about the safety of the water? Who, if anyone, makes a profit from the sale of tap water? Who, exactly, would be responsible for fulfilling these expectations?

Imagine you have purchased bottled water from a vending machine, and answer the following questions:

- Where did the water originate?
- Where did the plastic materials originate?
- How much did the bottled water cost compared to tap water? Who makes a profit, if anyone, from the sale of bottled water?
- Does drinking bottled water present less risk than drinking tap water? Explain the factors you have considered.
- What are the limitations of providing bottled water to meet the need for drinking water in Rwanda? How do cost, waste production, and social justice factor into this equation?

1.5 Definitions of Sustainability

The *Merriam-Webster Dictionary* defines ***"sustainable"*** as "capable of being sustained." This first dictionary definition does not shed much light on our discussion. The second definition listed begins to illuminate our topic: "of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged." Within this definition, we begin to see some key topics, including resource depletion and the term *damage* associated with nonsustainable practices.

The United States Environmental Protection Agency (EPA) provides a more useful working definition of sustainability:

> ***Sustainability*** *is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations. Sustainability is important to making sure that we have and will continue to have, the water, materials, and resources to protect human health and our environment. (Federal Register, 2009)*

Within the EPA definition, we see the words "harmony" and "protect" being applied to a relationship between humans and nature, which infers a moral virtue associated with sustainability. When we begin to think about sustainability in moralistic terms, we venture into the world of ethics and conflicting or sometimes contradictory moral quandaries.

For our simple analysis, we can describe ***morals*** as the values people adopt to guide the way they ought to treat each other. When we have a conflict between morals, we can use ethics to guide us toward the best outcome based on our ethical reasoning. ***Ethics***, therefore, provides a framework for making difficult choices when we face a problem involving moral conflict. These working definitions are much easier to understand when we evaluate a few of the following examples of the applications of an ethical code.

Most ethical thinking over the past 2,500 years has been a search for the appropriate ethical theory to guide our behavior in human–human relationships. Some of the most influential theories in Western ethical thinking, theories that are most defensible, are based on consequences or on acts. In the former, moral dilemmas are resolved on the basis of what the consequences are. If it is desired to maximize good, then the alternative that creates the greatest good is correct (moral). In the latter, moral dilemmas are resolved on the basis of whether the alternative (act) is considered good or bad; consequences are not considered.

The most influential consequentialist ethical theory is *utilitarianism*, described by Jeremy Bentham (1748–1832) and John Stuart Mill (1806–1873). In utilitarianism, the pain and pleasure of all actions are calculated and the worth of all actions is judged on the basis of the total happiness achieved, where happiness is defined as the highest pleasure/pain ratio. The so-called utilitarian calculus allows for the calculation of happiness for all alternatives being considered. To act ethically, then, is to choose the alternative that produces the highest level of pleasure and the lowest level of pain. Benefit/cost analysis can be considered to be utilitarian in its origins because money is presumed to equate with happiness.

A second group of ethical theories is based on the notion that human conduct should be governed by the morality of acts and that certain rules (such as "do not lie") should always be followed. These theories, often called *deontological* theories, emphasize the goodness of the act and not its consequence. Supporters of these theories hold that acts must be judged as good or bad, right or wrong, *in themselves*, irrespective of the consequences of these acts. An early system of deontological rules is the Ten Commandments, as these rules were meant to be followed *regardless of consequences*.

Possibly the best-known deontological system is that of Immanuel Kant (1724–1804), who suggested the idea of the ***categorical imperative***—the concept that one develops a set of rules for making value-laden decisions such that one would wish that all people obeyed the rules. Once these rules are established, one must always follow them; only then can that person be acting ethically because it is the act that matters. A cornerstone of Kantian ethics is the principle of *universalizability*, a simple test for the rationality of a moral principle. In short, this principle holds that, if an act is acceptable for one person, then *it must be equally acceptable for others*. Kant thus proposed that an act is either ethical or unethical if, when it is universalized, it makes for a better world. An example can be found in the *Code of Ethics for Engineers* shown in Box 1.4, which states "the engineer shall hold paramount the health, safety, and welfare of the public" (NSPE, 2007).

There are, of course, many more systems of ethics that could be discussed and that have relevance to the engineering and science professions, but it should be clear that traditional ethical thinking represents a valuable source of insight in one's search for a personal and professional lifestyle.

The concepts presented in both the EPA and Merriam-Webster definitions of sustainability suggest that conditions for the planet and humans inhabiting the Earth would be better if sustainable practices were adopted. However, the *Code of Ethics for Engineers* takes a human-centered view of a system, holding the "public" good in the highest regard. This might be thought of as an anthropocentric ethical framework in which nature is considered and valued based solely on the goods that nature can provide to humans or the "public."

Long before Kant, Aristotle appeared to support this anthropocentric view in his statement that "plants exist to give food to animals, and animals, to give food to men. . . . Since nature makes nothing purposeless or in vain, all animals must have

BOX 1.4 The National Society of Professional Engineers Code of Ethics for Engineers

Fundamental Canons: Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Source: National Society of Professional Engineers (NSPE) (2007) Code of Ethics for Engineers, Publication #1102. Alexandria, VA.

been made by nature for the sake of man" (Vesilind et al., 2010, p. 71). While the anthropocentric view is simple and concise, it does not seem to adequately reflect the feeling toward animals and nature held in most modern societies. For example, it is illegal in the United States and many other countries to encourage or promote animal fights for one's own pleasure.

This change in ethics was taking place in the Western world during the 1800s and was spearheaded by prominent writers and philosophers of the time. The growth of ethical arguments to include animals and nature has been termed *existentialist ethical thinking*, which extends the moral community to include creatures other than humans. Aldo Leopold articulated this viewpoint in *A Sand County Almanac* (1949). Leopold's work led to the development of a new ethical framework called the ***land ethic***, which encourages people to extend their thinking about communities to which we should behave ethically to include soil, water, plants and animals, or collectively, the land. Paul Taylor (1981, p. 207) describes a ***biocentric outlook*** that values all living things in Earth's community, so each organism is "a center of life pursuing its own good in its own way," and all organisms are interconnected. Arne Naess (1989, p. 166) took the biocentric outlook one step further when he wrote: "The right of all the forms to live is a universal right which cannot be quantified. No single species of living being has more of this particular right to live than any other species." The ethical framework in which humans have no greater importance than any other component of our world is sometimes referred to as deep ecology. The ***deep ecology*** ethic lies at the opposite side of the spectrum from an anthropocentric ethical code in evaluating the relationships between humankind and nature. However, most societies do not hold to the deep ecology worldview or paradigm. If modern societies did apply the deep ecology ethic, then modern medicine would not try to kill pneumonia bacteria with antibiotics while saving a human life.

So are there any ethical systems that modern societies have adopted? Certainly there are, and in the engineering profession, we are expected to uphold to specific ethical canons. Aldo Leopold suggests that "a thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." Certainly Leopold considered the human species to be part of this biotic community. Vesilind and Gunn (1998, p. 466) suggest another approach, which they describe as the ***environmental ethic***—"recognizing that we are, at least at the present time, unable to explain rationally our attitude toward the environment and that these attitudes are deeply felt, not unlike the feeling of spirituality." Furthermore, this approach embodies a sense of obligation to future generations of our species. When we consider the future conditions of our planet and species, we are using an intergenerational ethical model. If we consider future generations, we are perhaps making a moral choice to preserve and protect the things we value but have difficulty explaining.

Stewart Collis takes an agnostic approach to ethics:

> *Both polytheism and monotheism have done their work. The images are broken; the idols are all overthrown. This is now regarded as a very irreligious age. But perhaps it only means that the mind is moving from one state to another. The next state is not belief in many gods. It is not a belief in one god. It is not a belief at all—not a conception of the intellect. It is an extension of consciousness so that we may feel God. (Collis, 1954, p. 72)*

In his 2002 published letter, Pope John Paul II suggested an intergenerational and environmental ethical framework that blends advances in science and technology:

> *We therefore invite all men and women of good will to ponder the importance of the following ethical goals: To think of the world's children when we reflect on and evaluate our options for action. To be open to study the true values based on the natural law that sustain every human culture. To use science and technology in a full and constructive way, while recognizing that the findings of science have always to be evaluated in the light of the centrality of the human person, of the common good and of the inner purpose of creation. Science may help us to correct the mistakes of the past, in order to enhance the spiritual and material well-being of the present and future generations. It is love for our children that will show us the path we must follow in the future.*

Throughout the ages we have blended our ethical, moral, and spiritual beliefs in an effort to apply definitions to the actions we take both individually and as a species. The most commonly referenced definition of sustainability is derived from the Brundtland Commission's report on practices for sustainable development and approaches to reduce the number of people living in poverty. The report of this commission, called *Our Common Future*, defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

Within this definition of sustainability, we see that human needs are placed somewhat above the needs of other animals and plants. However, this definition recognizes the inherent value of the natural world and the role of the natural world in meeting the basic needs of humanity. Furthermore, this definition relies heavily on intergenerational equity to protect the natural world so that future generations will not live in an impoverished planet. Engineers, scientists, technicians, and policymakers are charged with the role of identifying technologies that can meet these needs and improve the standard of living on the planet, in spite of significant resource constraints.

Sustainable design is the design of products, processes, or systems that balance our beliefs in the sanctity of human life and promote an enabling environment for people to enjoy long, healthy, and creative lives, while protecting and preserving natural resources for both their intrinsic value and the natural world's value to humankind. Engineers who practice sustainable design must have a grasp of the social, economic, and environmental consequences of their design decision and a thorough

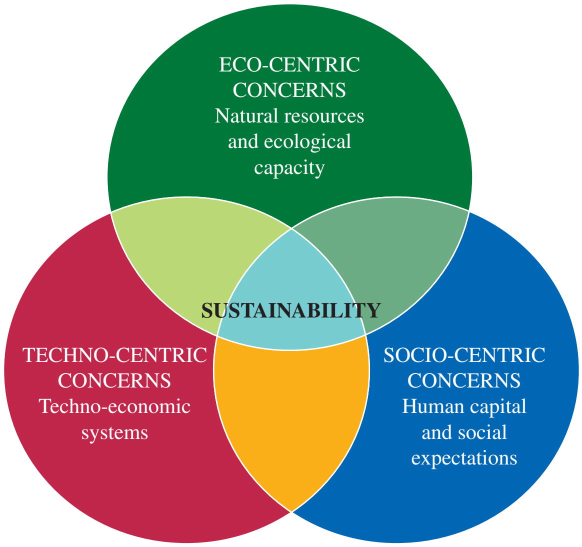


FIGURE 1.17 Sustainable systems are illustrated by those systems that balance eco-centric, techno-centric, and socio-centric concerns.

Source: Based on Elkington, J., "Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development," *California Management Review* 36, no. 2 (1994): 90–100.

understanding of the scientific principles of the technology available, as illustrated in Figure 1.17. The EPA defined sustainability as "the continued protection of human health and the environment while fostering economic prosperity and societal well-being" (Fiksel et al., 2012, p. 5). The only way we can actually achieve sustainable development is for scientists, engineers, technicians, and policymakers to develop and apply more efficient technologies that improve the standard of living and are adaptable to the global marketplace. Furthermore, we need to identify and relate the limitations of our natural resources to our desire for continual development.

ACTIVE LEARNING EXERCISE 1.3 **Sustainable Policy**

Write down as many sustainability policies or regulations as you can. These might be laws related to the environment, health, or resources—such as limitations on fish catch, and so on. How would we engineer a future for more people, more stuff, and more energy that is all available for a longer time (into the future)? Describe how you might develop a sustainability policy for one aspect of something important in your life, and explain how that policy might be applied locally, nationally, and internationally.

In 1948, an air pollution event in Donora, Pennsylvania, resulted in the deaths of 20 people and thousands of pets as people were ordered to evacuate their homes and leave their pets behind. The fact that pets suffered greatly in the Donora events has been almost completely ignored by all accounts. Why do you think this information is largely ignored? Is this an ethically acceptable behavior? Why are we mostly concerned about only our own species?

1.6 Populations and Consumption

The relationship between consumption of a natural resource, waste production, and regeneration of that resource is described mathematically as the carrying capacity. Dr. Paul Bishop (1999) defines the ***carrying capacity*** as "the maximum rate of resource consumption and waste discharge that can be sustained indefinitely in a given region without progressively impairing the functional integrity and productivity of the relevant ecosystem." A sustainable economic system operating within the Earth's carrying capacity demands the following.

The usage of renewable resources is not greater than the rates at which they are regenerated.

The rates of use of nonrenewable resources do not exceed the rates at which renewable substitutes are developed.

The rates of pollution or waste production do not exceed the capacity of the environment to assimilate these materials.

In order to calculate the carrying capacity of the Earth and its resources, we must be able to make some predictions about human population and consumption patterns. The world's steadily increasing population has put stress on available natural resources, including food, water, energy, phosphorus, fossil fuels, and precious metals. Both human population and consumption of resources are *increasing* at an *increasing rate.* Thus, linear mathematical models do not accurately estimate population trends; instead, we must apply an exponential model to estimate population growth and resource consumption patterns.

Exponential growth occurs when the rate of change, dA/dt, is proportional to the instantaneous value of A at some time t:

$$\frac{dA}{dt} = kA \tag{1.7}$$

We can integrate this expression with respect to time, which yields

$$A_{(t)} = A_o \exp(k(t - t_o)) \tag{1.8}$$

where A_o is the value of A at our initial time, t_o. The variable k is the exponential growth rate constant and typically has units of [1/time].

EXAMPLE 1.3 Historical World Population Growth

The world's population was approximately 370 million in AD 1350. By the year 1804, the world's population had reached 1 billion people. Find the exponential growth rate during that time period.

The term k in Equation (1.8) represents the population growth constant. We can rearrange Equation (1.8) to solve for the rate constant:

$$A_{(t)} = A_o \exp(k(t - t_o))$$

$$\ln\left(\frac{A_{(t)}}{A_o}\right) = k(t - t_o)$$

$$k = \left(\ln\left(\frac{A_{(t)}}{A_o}\right)\right)\left(\frac{1}{(t - t_o)}\right)$$