Systems Science

for Engineers and Scholars

Avner Engel

WILEY

Cover image: The Southern Ring is a planetary nebula showing the remnants of a dying Sun-like star. The nebula, composed of gas and interstellar dust, is located some 2500 light-years from Earth and is nearly half a light-year in diameter. The bright star near the center is a companion of the dead star whose transformation has ejected the nebula's gas and dust shells over thousands of years. The NIRCam instrument onboard NASA's (National Aeronautics and Space Administration) James Webb space telescope obtained this image in 2022 (Image: NASA).

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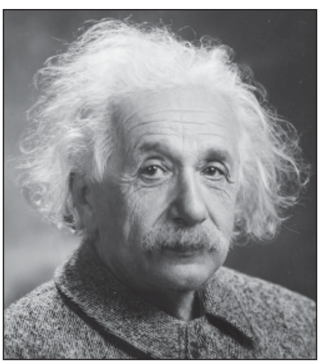
To my wife Rachel and sons Ofer, Amir, Jonathan, and Michael.



"If you can't explain it to a six-year-old, you don't understand it yourself."

"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."

—Albert Einstein

Table of contents

Preface

This book describes the fundamentals of systems science and how engineers, engineering students, and other scholars can put these concepts into practical use at work and in their personal lives. Systems science is an interdisciplinary field that studies the foundation of systems in nature and society. It suggests that the Universe is composed of systems or systems of systems, all of which possess common intrinsic attributes.

Along this line, systems science aims to determine systemic similarities among different disciplines (e.g., engineering, physics, biology, economics, mathematics) and to develop valuable models that apply to many fields of study. The advantage of this approach is that people, and in our case, engineers and scholars, can obtain answers to problems by studying and adopting ideas from different domains.

Engineers often seek speedy solutions to technical problems within a relatively restricted mindset. Under this ethos, engineers can be proud of many achievements throughout history. However, this book provides engineers with powerful means to enhance their professional and personal abilities by utilizing holistic and multidisciplinary elements inherent in systems science theory.

The book identifies 10 fundamental systems science principles that open engineers' horizons to various domains from which they can conclude practical insights about their areas of interest. For example, one systems science fundamental deals with interactions between different systems. Consider an engineer who examines a particular interface within a technical system. He may embrace a holistic view in his system design by adopting biological interactions among species. Biology researchers recognize six relationship types (i.e., competition, predation, herbivory, mutualism, parasitism, and commensalism). Thus, by adopting ideas from biology, this engineer can open his design to many creative alternatives.

In brief, this book expresses complex ideas related to holistic and interdisciplinary learning in a concise and easy-to-grasp manner, with many examples and graphics. As a result, the book opens new perspectives and provides practical guidance to engineers and scholars wishing to implement systems science concepts. The book contains the following four parts:

1. **Part 1: Facets of Systems Science and Engineering.** This part starts with a preface to systems science. It defines 10 fundamental principles of systems science: universal context, boundary, hierarchy, interactions, change, input/output, complexity, control, evolution, and emergence. Multiple examples

illuminate each principle. This part also describes ideas about systems thinking, the philosophy of engineering, and systems engineering. Finally, this part brings forth an analysis of an engineered versus a biological system. This analysis emanates from one of systems science's promises to transcend individual disciplines by obtaining knowledge from well-known domains to elucidate less-known domains.

2. **Part 2: Holistic Systems Design.** This part provides fresh, holistic thinking about the system context, which is, by definition, the environment of a system of interest (SoI). Such a view recognizes that systems' context influences SoI in wide, often unpredictable, and sometimes disastrous ways. This concept is illustrated by an extensive example of an unmanned air vehicle (UAV) system of interest in its all-inclusive context. This system context includes natural systems, social systems, research systems, formation systems, sustainment systems, business systems, commercial systems, financial systems, political systems, legal systems, cultural systems, and biosphere systems. Ultimately, this part intends to motivate engineers and designers to create resilient systems that can withstand their contexts' uncertain behavior.
3. **Part 3: Global Environment and Energy: Crisis and Action Plan.** Today, the global environmental and energy crises seem to be humankind's most challenging, systemic predicaments. This part analyzes the environmental crisis regarding past and present global transformation and its environmental predicament. This part proceeds with a proposed systemic, no-nonsense ecological action plan to sustain the Earth's system and human society. Similarly, the global energy crisis is analyzed, including the current global energy status, energy return on investment (EROI), and the impact of renewable energy systems. Again, this part proceeds with a no-nonsense proposed systemic energy action plan for the global energy crisis. This action plan deals with renewable, fossil, and fission energy. In addition, it describes short-term future energy options, including small modular reactors (SMR), and long-term future energy options, including nuclear fusion.
4. **Part 4: More Systems Science for Engineers and Scholars.** This part contains independent articles showing how engineers can utilize systems science creatively. This part includes (1) engineering and systemic psychology, (2) delivering value and resolving conflicts, (3) multi-objective, multi-agent decision-making, (4) systems engineering using category theory, (5) holistic risk management using systems of systems failures (SOSF) methodology, and (6) systemic accident and mishap analysis.

Acknowledgments

The author seeks to acquaint engineers and scholars with facets of systems science. To achieve this objective, the author has drawn upon his engineering experience, communicated with many people, and synthesized information from many sources such as books, articles, blogs, etc. Several researchers have provided permission to incorporate adapted portions of their writings (e.g., texts, images, and ideas) within this book. The author is deeply indebted to these people and institutions:

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Avner Engel
Tel Aviv, Israel

Part I

Facets of Systems Science and Engineering

1

Introduction to Systems Science

1.1 Foreword

1.1.1 The Book

This book describes the fundamental principles of systems science and how engineers, engineering students, and other scholars can put its concepts into practical use at work and in their personal lives. Systems science[1] is an interdisciplinary field that studies the foundation of systems in nature and society. It suggests that the universe is composed of systems or systems of systems, all of which possess common intrinsic attributes.

Along this line, systems science aims to determine systemic similarities among different disciplines (e.g., engineering, physics, biology, economics, mathematics) and to develop valuable models that apply to many fields of study. The advantage of this approach is that people, and in our case, engineers, can obtain answers to problems by studying and adopting ideas from different domains.

Engineers often seek speedy solutions to technical problems within a relatively restricted mindset. Under this ethos, engineers can be proud of many achievements throughout history. However, this book provides engineers with powerful means to enhance their professional and personal abilities by utilizing holistic and multidisciplinary elements inherent in systems science theory.

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1 A system is: "an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not." Sources: Systems Engineering and System Definitions, ISO/IEC/IEEE 15288:2015.

Science is: "the systematic study of the structure and behavior of the physical and natural world through observation, experimentation, and the testing of theories against the evidence obtained." *The Dictionary*.

Systems Science for Engineers and Scholars, First Edition. Edited by Avner Engel.

The book identifies 10 fundamental systems science principles that open engineers' horizons to various domains from which they can conclude practical insights about their areas of interest. For example, one systems science fundamental principle deals with interactions between different systems. Consider an engineer who examines a particular interface within a technical system. He may embrace a holistic view in his system design by adopting biological interactions among species. Researchers in biology recognize six types of relationships (i.e., competition, predation, herbivory, mutualism, parasitism, and commensalism). Thus, by adopting ideas from biology, this engineer can open his design to many creative opportunities.

In brief, this book expresses complex ideas related to holistic and interdisciplinary learning in a concise and easy-to-grasp manner with many examples and graphics. As a result, the book opens new perspectives and provides practical guidance to engineers and scholars wishing to implement systems science concepts.

1.1.2 The Overall Structure of the Book

Figure 1.1 depicts the book's overall structure, consisting of the front matter, the main book's body, and the back matter.

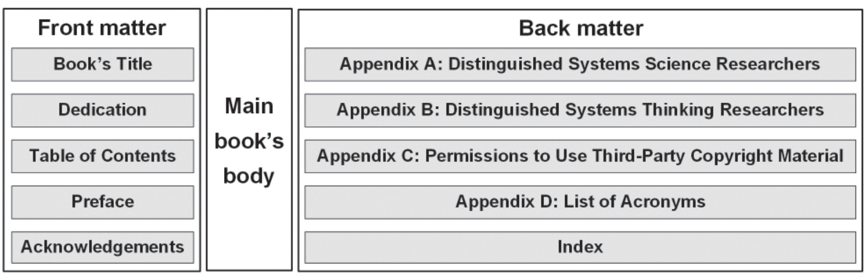

Figure 1.1 Overall structure of the book.

1.1.3 The Structure of the Book's Main Body

Figure 1.2 depicts the structure of the main body of the book. It is divided into four parts as follows:

- Part 1: Facets of Systems Science and Engineering
- Part 2: Holistic Systems Design
- Part 3: Global Environment and Energy: Crisis and Action Plan
- Part 4: More Systems Science for Engineers and Scholars

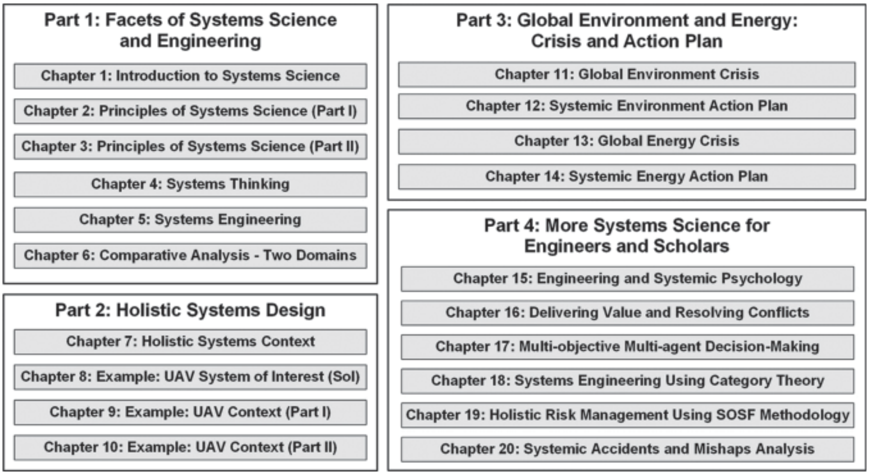

Figure 1.2 Structure of the book's main body.

1.1.3.1 Part 1: Facets of Systems Science and Engineering

- **Chapter 1: Introduction to Systems Science.** This chapter provides a preface to the book, followed by a discussion of humanity's challenges. It then briefly encapsulates systems science and describes early systems pioneers. Finally, this chapter presents some criticisms of systems science and relevant responses.
- **Chapter 2: Principles of Systems Science (Part I).** This chapter and the next one define the 10 fundamental systems science principles. For clarity, these principles are presented in two chapters. This chapter describes the following principles: (1) universal context, (2) boundary, (3) hierarchy, (4) interactions, and (5) change. Numerous examples describe each principle.
- **Chapter 3: Principles of Systems Science (Part II).** This chapter describes the following principles: (6) input/output, (7) complexity, (8) control, (9) evolution, and (10) emergence. Again, numerous examples describe each principle.
- **Chapter 4: Systems Thinking.** This chapter discusses the fundamental concepts of systems thinking and the iceberg model of systems thinking. It then explores systems thinking as a system in its own right. Finally, the chapter elaborates on various barriers to systems thinking and describes early systems thinking pioneers.
- **Chapter 5: Systems Engineering.** This chapter brings forth illuminating ideas on the philosophy of engineering. It then describes systems engineering concepts, culminating in systems engineering deficiencies, systems' pathologies, and infamous engineered systems failures and disasters.

- **Chapter 6: Comparative Analysis - Two Domains.** This chapter presents a comparative analysis of biological versus engineered systems. The analysis emanates from one of systems science's promises to transcend disciplines by obtaining knowledge about less-known domains utilizing analogies from well-known domains.

1.1.3.2 Part 2: Holistic Systems Design

- **Chapter 7: Holistic Systems Context.** This chapter provides a holistic description of the systems context, which is, by definition, the environment of a system of interest (SoI). A more holistic view of systems contexts recognizes that the broad environment of SOIs has myriad and settled influences over SOIs. Many spectacular engineering failures can be traced to systems whose designers ignored such consequences. Thus, this chapter covers renewed thinking about the systems context and its components.
- **Chapter 8: Example: UAV System of Interest (SoI).** This chapter and the following two chapters elucidate the concept of holistic systems contexts. This chapter provides a compressive example of an unmanned air vehicle (UAV) system of interest (SoI). The UAV description focuses on the 10 systems science fundamental principles: universal context, boundary, hierarchy, interactions, change, input/output, complexity, control, evolution, and emergence.
- **Chapter 9: Example: UAV Context (Part I).** This chapter illuminates the holistic nature of SoI context issues through the UAV system described earlier. Specific topics related to the UAV systems context are presented in two chapters. First, this chapter describes the following UAV system contexts: (1) natural systems, (2) social systems, (3) research systems, (4) formation systems, (5) sustainment systems, (6) business systems, and (7) commercial systems.
- **Chapter 10: Example: UAV Context (Part II).** This chapter continues to illuminate the holistic nature of SoI context issues through the UAV system described earlier. This chapter describes the following UAV system contexts: (8) financial systems, (9) political systems, (10) legal systems, (11) cultural systems, and (12) biosphere systems.

1.1.3.1 Part 3: Global Environment and Energy: Crisis and Action Plan

- **Chapter 11: Global Environment Crisis.** Nowadays, humanity faces many global predicaments. One of the most challenging, systemic global issues is the environmental crisis. This chapter describes and systemically analyzes it. This analysis includes past and present global transformation and the crisis' environmental predicament.
- **Chapter 12: Systemic Environment Action Plan.** Currently, little is being done about the environmental problem. However, this indifferent attitude will change drastically as life on this planet becomes more and more unbearable for more and more people. Then governments, environmental scientists, engineers, and the public will unite in carrying out measures to combat global

environmental threats to the human species. This chapter provides a systemic action plan for this massive ecological threat to humankind. This plan includes sustaining the Earth's system and sustaining human society.

- **Chapter 13: Global Energy Crisis.** As mentioned before, humanity faces many global predicaments. The second most challenging systemic global issue is the global energy crisis. This chapter describes and systemically analyzes the global energy crisis. This description includes the current global energy status, energy return on investment (EROI), and the effect of renewable energy systems.
- **Chapter 14: Systemic Energy Action Plan.** This chapter provides a systemic action plan for the global energy crisis. This description includes a discussion regarding the global energy dilemma and what can be done about renewable energy, fossil energy, and fission reaction energy. In addition, the chapter describes short-term future energy, including small modular reactors (SMR), and long-term future energy, including nuclear fusion.

1.1.3.2 Part 4: More Systems Science for Engineers and Scholars

- **Chapter 15: Engineering and Systemic Psychology.** This chapter provides systemic links between key psychological features in systems engineering. In particular, it describes schema theory and cognitive biases, which sometimes lead to failed design, building, or systems operations. This linkage is illustrated by several spectacular systems failures, including the Bay of Pigs fiasco (1961), the disastrous 747 collision at Tenerife (1977), the space shuttle *Columbia* disaster (2003), BP's *Deepwater Horizon* oil spill (2010), and the collapse of the Morandi Bridge in Genoa (2018). The chapter then covers ways to undertake cognitive debiasing.
- **Chapter 16: Delivering Value and Resolving Conflicts.** Systems must sustain their ability to deliver value to stakeholders throughout their life. Therefore, delivering systems value requires identifying those things that enhance value to all stakeholders. Likewise, conflicts among developers and builders of systems and their resolutions have been the subjects of many studies and other research. This chapter systematically analyzes two related topics: (1) delivering systems value and (2) conflict analysis and resolution.
- **Chapter 17: Multi-objective, Multi-agent Decision-Making.** Multi-objective, multi-agent (MOMA) decision-making aims to optimize the policies of individual stakeholders concerning multiple objectives within the multistakeholder environment. These decisions should consider the possible trade-offs between conflicting objective functions and stakeholders' desires. The chapter includes the following issues: (1) multi-objective multi-agents, (2) representation of systems activities, (3) key types of systems activities, and (4) three illustrative examples.

- **Chapter 18: Systems Engineering Using Category Theory.** Systems engineers own systems components' conceptual, logical, and physical integration throughout engineered projects. Therefore, adopting a collaborative mindset is crucial because integration occurs first and foremost among people and only afterward among systems and technologies. This chapter describes systems engineering using category theory. It includes the following elements: (1) defining the problem, (2) brief background on category theory and systems engineering, (3) an example of designing an electric vehicle, (4) category theory as a systems specification language, (5) categorical multidisciplinary collaborative design, and (6) the categorical design processes.
- **Chapter 19: Holistic Risk Management Using SOSF Methodology.** The predominant worldview on risk management in current engineering practice is that system failure risks should be addressed during the design phase. However, such an approach excludes proactive handling of emerging risks throughout the systems' life, leading to repeated failures. This chapter uses a systems of systems failures (SOSF) methodology to describe systemic risk management. It includes the following elements: (1) limitations of current risk management practices, (2) features of SOSF, (3) an example of holistic risk management and failure classes, and (4) an example of a synthetic SOSF risk management.
- **Chapter 20: Systemic Accidents and Mishaps Analyses.** This chapter describes different accident causation models, which explain how accidents happen. Based on systems theory, one systemic accident model that reflects the current complex sociotechnical environment is the systems-theoretic accident model and processes (STAMP). The chapter explains the systemic nature of the STAMP accidents and mishaps model. It includes the following elements: (1) basic accident and mishap concepts; (2) classification of accident causation models; (3) the STAMP model, sociotechnical failure mechanisms, and procedures; and (4) causal analysis system theory (CAST) procedures and an example of CAST analysis involving the collision of two CH-53 helicopters.

1.1.4 Disclaimer

The author seeks to acquaint engineers, systems engineers, and other scholars with reasonably acceptable facets of systems science. To achieve this objective, the author drew on his engineering experience; communicated with many people; and synthesized information from many sources, including books, articles, blogs, and the like (giving credit where credit is due). In addition, a bibliography is placed at the end of each chapter covering invaluable sources for a deeper understanding of the various issues discussed in this book. The author gained much knowledge from these resources and is indebted to the individuals, researchers, and experts who created them. Readers should note that the sources of all third-party images and texts, as well as permissions to use them, are provided in Appendix C: Permissions to Use Third-Party Copyright Material.

1.2 Critical Humanity Challenge

According to Rousseau et al. (2016), the founders of general systems theory (systems science today) were mainly concerned with the far-reaching risks to human civilization of the proliferation of nuclear weapons along with looming environmental issues. In addition, they were worried about losing meaning, value, and purpose in human lives. They maintained that science and philosophy relied unrealistically on simplistic models of reductionism and proposed that a new systems theory would provide a more appropriate and enabling paradigm. Sadly, the approach has made little progress, and human existential problems are more significant than ever.

Nevertheless, many scientists believe systems science methodology offers the best-coordinated opportunity to deal with intractable problems. One such issue relates to the global environmental challenge, which, if left unchecked, threatens the existence of humanity in the not-too-distant future.

In their groundbreaking paper "A Safe Operating Space for Humanity,"[2] published in 2009, some 30 eminent European, American, and Australian researchers tried to identify and quantify nine planetary boundaries that should not be crossed to prevent unacceptable environmental change.

These nine planetary biophysical boundaries are (1) climate change, (2) ocean acidification, (3) stratospheric ozone depletion, (4) biogeochemical flows, (5) global freshwater use, (6) deforestation and other land use changes, (7) biodiversity loss, (8) atmospheric aerosol loading, and (9) chemical pollution.

According to the authors, as of 2009, three of these nine planetary biophysical boundaries had already been breached: (1) climate change, (2) rate of biodiversity loss, and (3) changes to the global nitrogen cycle. These findings could induce disastrous consequences for humanity.

Figure 1.3 depicts the model proposed by the study on a safe operating space for humanity. The inner circle represents a safe operating space for nine planetary systems, and the red wedges represent an estimate of the year 2009 position for each variable.

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2 Rockstrom J. et al. (2009, Sept.). A safe operating space for humanity. *Nature* 461: 472–475. https://www.nature.com/articles/461472a.pdf. Accessed Jan. 2023.

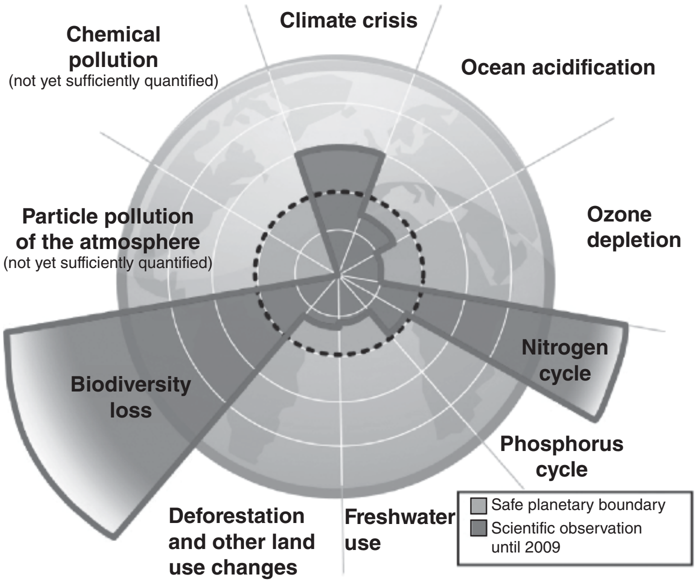

Figure 1.3 Safe operating space for humanity (Rockstrom et al., 2009).

These critical problems require the concerted efforts of governments throughout the world. From a scientific standpoint, systems scientists could provide essential inputs to resolve or mitigate these significant problems. An updated research, "Earth beyond six of nine planetary boundaries" (Richardson et al., 2023), was released recently, indicating a significant deterioration in the current earth's environmental conditions. A description of this new research is discussed in Chapter 11.

1.3 Systems Science in Brief

1.3.1 About Science

According to UNESCO (United Nations Educational, Scientific and Cultural Organization),[3] science is the most significant collective human endeavor. "It contributes to ensuring longer and healthier life, monitors our health, provides

3 The 4 Pillars of Education by UNESCO. See The 4 Pillars of Education by UNESCO: You are Mom. https://youaremom.com/parenting/raising-a-child/4-pillars-education-unesco/.Accessed: Jan. 2023.

medicine to cure our diseases, alleviates aches and pains, helps us to provide water for our basic needs—including our food, provides energy, and makes life more fun, including sports, music, entertainment, and the latest communication technology. Last, but not least, it nourishes our spirit. Science provides logical solutions for everyday life and helps us answer the universe's mysteries."

Modern science is typically divided into two major branches: the empirical sciences, which study nature in the broadest sense, and the formal sciences, which study abstract concepts. The empirical sciences are further divided into natural sciences and social sciences. Natural sciences describe, predict, and seek to understand natural phenomena based on empirical evidence from observations and experiments. They may be further divided into two main branches: physical sciences and life sciences. Finally, social sciences are concerned with the relationships among individuals and societies within the human species.

In contrast, formal sciences study formal systems,[4] which are derived by reasoning from self-evident propositions. Applied science, therefore, is the application of scientific knowledge to obtain practical objectives. The relationships between the branches of science are shown in Figure 1.4.

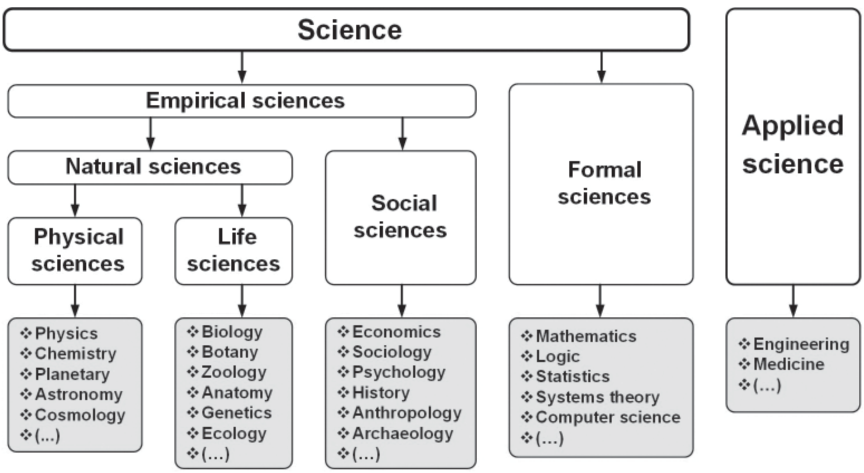

Figure 1.4 Relationships between the branches of science.

Figure 1.5 and Table 1.1 depict some of the most outstanding scientists of antiquity and modern times and their momentous scientific discoveries that have affected much of humanity.

4 Derived from https://en.wikipedia.org/wiki/Science. Accessed: Jan. 2023.

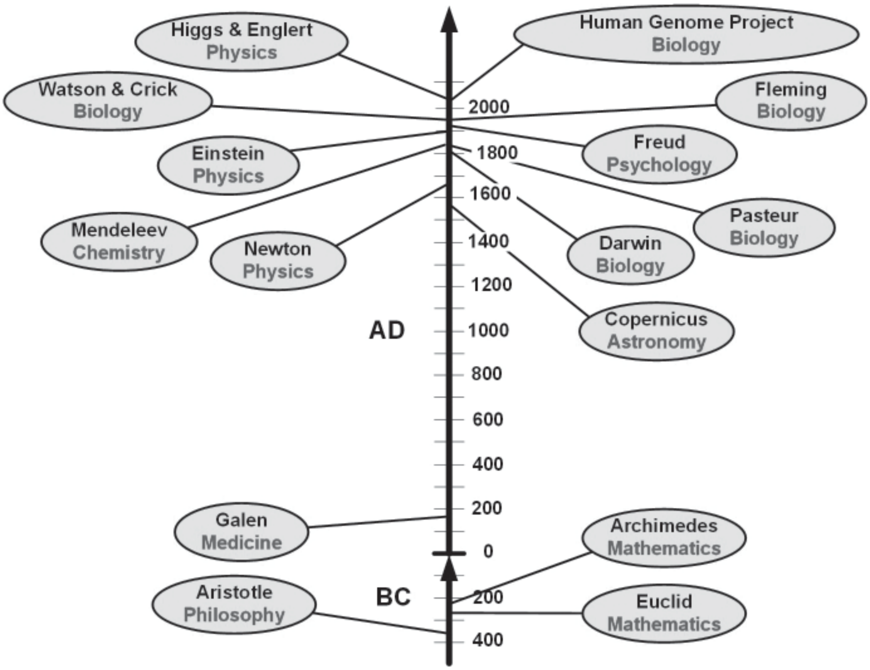

Figure 1.5 Outstanding scientists of antiquity and modern times.

Table 1.1 Momentous scientific discoveries.

Person	Domain	Scientific achievement	Year
Aristotle (384–322 BC)	Philosophy	Philosophical ideas and contributions to physics are still being taught for almost two millennia	350 BC
Euclid (325–270 BC)	Mathematics	Famous mathematical, astronomical, navigation, and other scientific works valid for more than two millennia	300 BC
Archimedes (287–212 BC)	Mathematics	Extensive calculus, statics, hydrostatics, and geometrical theorems valid for more than two millennia	250 BC
Galen (129–216)	Medicine	A flawed medical doctrine that dominated Western and Arab practices for 1500 years	170
Nicolaus Copernicus (1473–1543)	Astronomy	Heliocentrism: the sun is stationary at the center of the solar system, and planets revolve around it	1543