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.

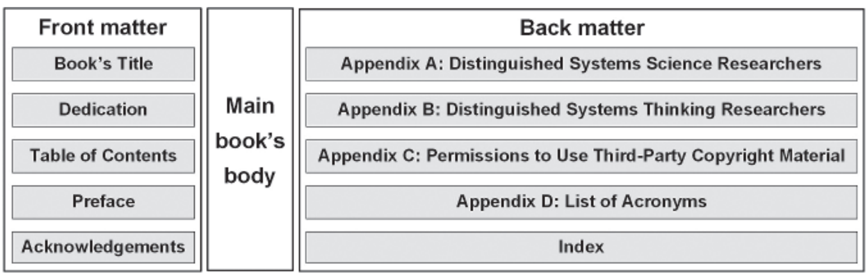

Figure 1.1 Overall structure of the book.

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

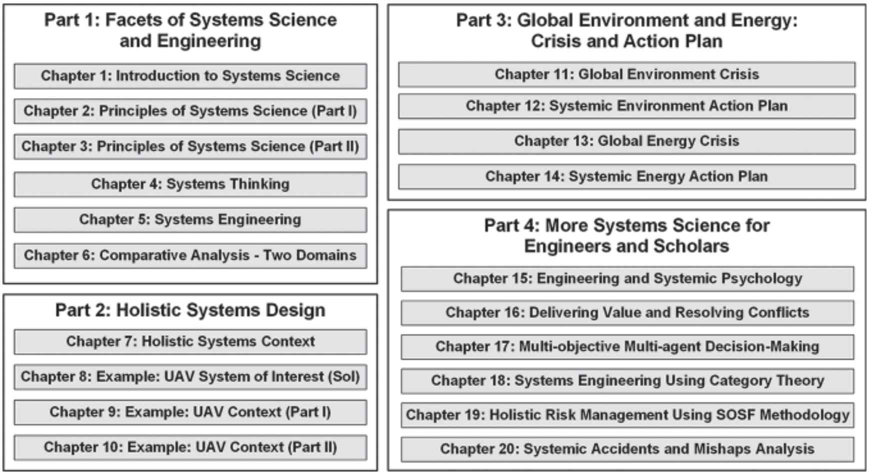

Figure 1.2 Structure of the book's main body.

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.

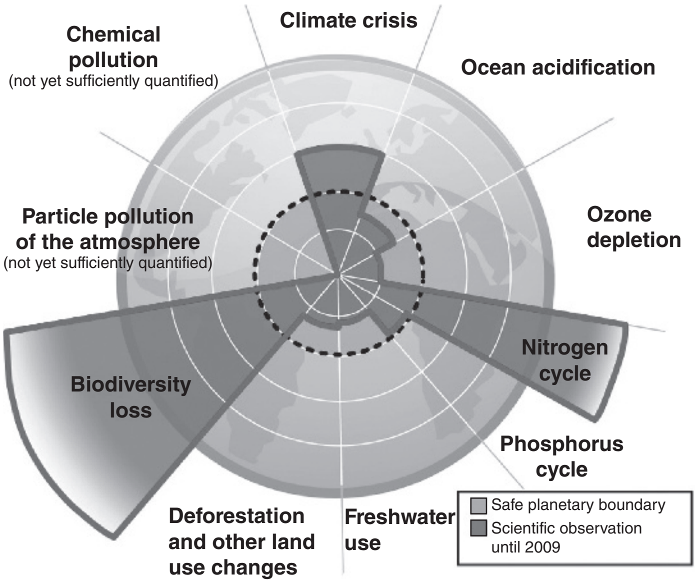

Figure 1.3 Safe operating space for humanity (Rockstrom et al., 2009).

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.

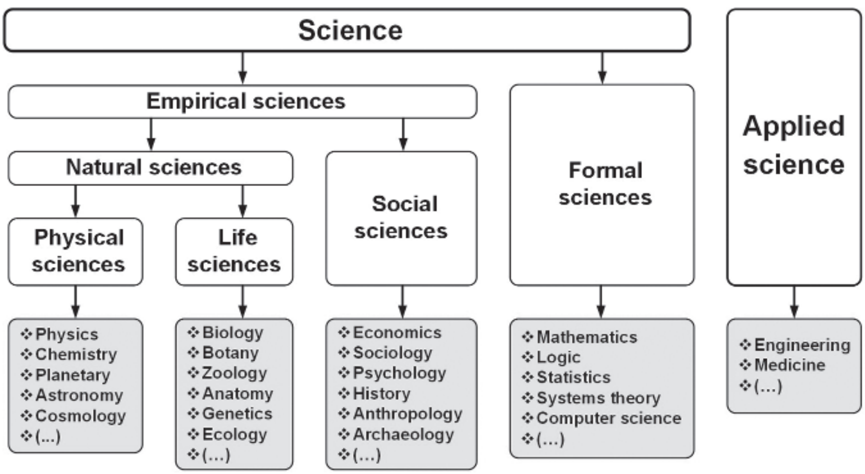

Figure 1.4 Relationships between the branches of science.

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.

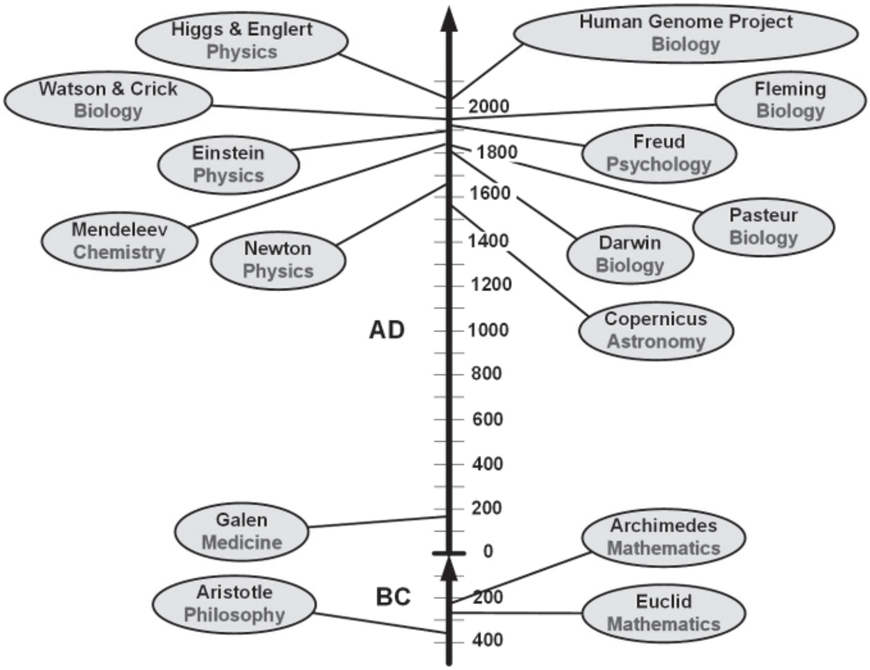

Figure 1.5 Outstanding scientists of antiquity and modern times.

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

Table 1.1 (Continued)

Person	Domain	Scientific achievement	Year
Isaac Newton (1642–1726)	Physics	Newton's three laws of motion and Newton's law of universal gravitation	1664
Charles Darwin (1809–1882)	Biology	Theory of evolution/natural selection	1859
Dmitry Mendeleev (1834–1907)	Chemistry	Periodic Table of chemical elements	1864
Louis Pasteur (1822–1895)	Biology	Diseases caused by microorganisms that can be killed by heat and disinfectants	1881
Albert Einstein (1879–1955)	Physics	Einstein's special and general relativity theories and Einstein's mass–energy equivalence $E = mc^2$	1905
Sigmund Freud (1858-1939)	Psychology	Freud's psychoanalysis: clinical method for treating psychopathology	1910
Alexander Fleming (1881–1955)	Biology	First antibiotic substance: penicillin	1928
James Watson (1928–) and Francis Crick (1916–2004)	Biology	Double helix structure of the DNA molecule	1953
Human Genome Project (HGP)	Biology	Mapping the human genome	1990–2003
Peter Higgs (1929–) and Francois Englert (1932–)	Physics	Proposing the Higgs boson and its subsequent discovery at the European Council for Nuclear Research (CERN) Large Hadron Collider (LHC)	1960; 2012

1.3.2 Silo Effects

Conventional science adheres to the division of labor by specialization in specific and narrow fields of endeavor. Along this line, academia and other research institutes are organized into discrete faculties and departments, making responsibilities more explicit. For example, the human body is organized into specialized organs.

Accordingly, medical caretakers require specializations, each within a relatively narrow sphere of interest. Furthermore, most scientists are trained to be independent and to focus on precise and focused targets. The great motivation is to stick to a problem and dig deep enough until, eventually, one may find something valuable.

This arrangement often leads academic researchers to ignore relevant research within other scientific domains. As a result, much knowledge is sequestered within individual academic faculties, departments, or small groups of researchers. This type of "silo mentality" tends to create bureaucratic rivalry, tunnel vision, and blind spots, which reduce the potential efficiency of the scientific endeavor. In short, a silo mentality causes excessive compartmentalization, inhibiting communication among domains and stifling innovation (Figure 1.6).

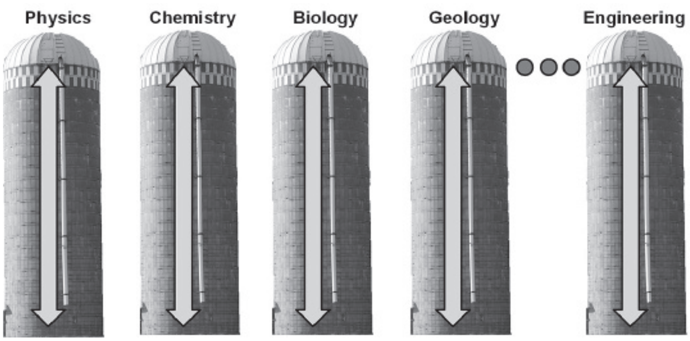

Figure 1.6 Conventional scientific "silo view" (image inspired by Len Troncale's writings).

1.3.3 Systems Science[5]

Systems science is an interdisciplinary field. It studies the essence of systems in nature, society, technology, and science. More specifically, systems science attempts to develop a scientific foundation that applies to all areas of science. This foundation includes the physical sciences (e.g., physics, chemistry), life sciences (e.g., biology, botany), social sciences (e.g., economics, sociology), formal sciences (e.g., mathematics), and applied sciences (e.g., engineering, medicine). In short, systems scientists consider everything in the universe as being composed of systems or systems of systems. Furthermore, all systems share common attributes, characteristics, and organizational and behavioral principles. Therefore, understanding these universal aspects is the basis for understanding the universe. In other words, understanding the principles of systems science can guide the study of any specific kind of system (Figure 1.7).

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5 Parts of this section were inspired by the writings of George Mobus, Professor Emeritus, School of Engineering & Technology, University of Washington, Tacoma.

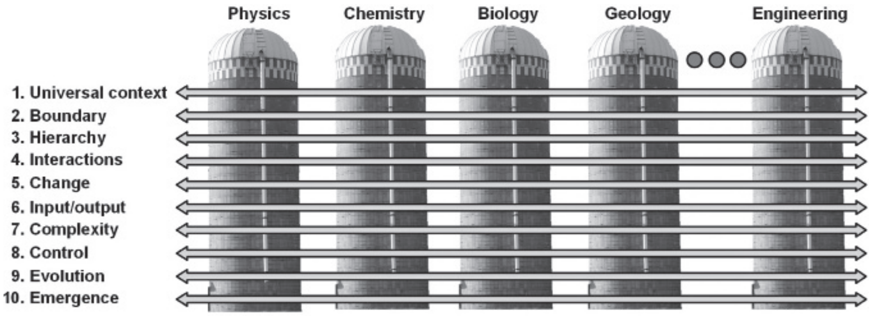


Figure 1.7 Systems science fundamental view (image inspired by Len Troncale's writing).

Table 1.2 defines a set of fundamental principles of systems science that operate overall knowledge domains.

Table 1.2 Systems science fundamental principles.[6]

#	Principle	Short Description
1.	Universal context	The universe is composed of systems and systems of systems.
2.	Boundary	All systems have a boundary that demarcates the system from its context (environment).
3.	Hierarchy	All systems are entities organized in structural and functional hierarchies.
4.	Interactions	All systems contain networks of relations among their components and/or with their context.
5.	Change	All systems change and transform continuously in many dimensions and on multiple time scales.
6.	Input/output	All systems receive information, energy, and/or matter from their context, process it, and then transmit the result to their context.
7.	Complexity	All systems exhibit various kinds and levels of complexity.
8.	Control	All systems have an internal regulatory mechanism to achieve long-term stability or controlled oscillation.
9.	Evolution	Living systems evolve to harmonize with their dynamic context. Inanimate systems are modified to satisfy their dynamic context.
10.	Emergence	All systems exhibit properties or behaviors their parts do not possess.

6 Adapted with modifications from Mobus and Kalton (2015).

1.3.4 Typical Engineered System

There are many definitions of systems. Among them, a broad yet lean and concentrated definition is "A system is a collection of interrelated parts that, by the relationships between them, do things its parts cannot do on their own" (Martin et al., 2019). An example of a simple engineered system in its context (environment) is depicted in Figure 1.8.

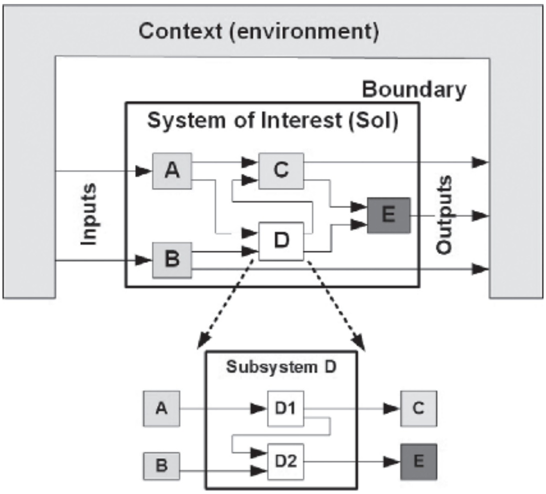


Figure 1.8 Example of a simple engineered system in its context (environment).

1.3.5 The Ad Hoc Collaboration

Shortcomings of silo thinking have been discussed since the term *functional silo syndrome* was coined by Phil Ensor in 1988. One response to this situation involves global scientific collaboration. Researchers collaborate to complement their knowledge and skills and access funding and specialized equipment. In principle, scientists can learn from, work with, and foster global collaborative partnerships with scientists across multiple research disciplines. Also, from a researcher's point of view, collaboration with other scientists combines to create value exceeding the sum of its parts. Mainly, it mitigates the one way of thinking constraint.

For example, let us consider the global environmental challenge. First, there are physical sciences—physics, chemistry, and the like. Second, there are life sciences—biology, botany, ecology, and so on. Third, there are social science—economics, sociology, and the like. How are we going to manage this multidimensional problem? Also, we should consider the engineering aspects: How do we design more efficient and environmentally friendly infrastructure systems? Having collaborating experts from many disciplines means the challenge can be assailed from all sides simultaneously, giving humanity a chance to resolve this problem. A global science map based on citing similarities among SPRU[7] subject categories is depicted in Figure 1.9. Each node represents a discipline, and the connecting lines represent similarities among disciplines.

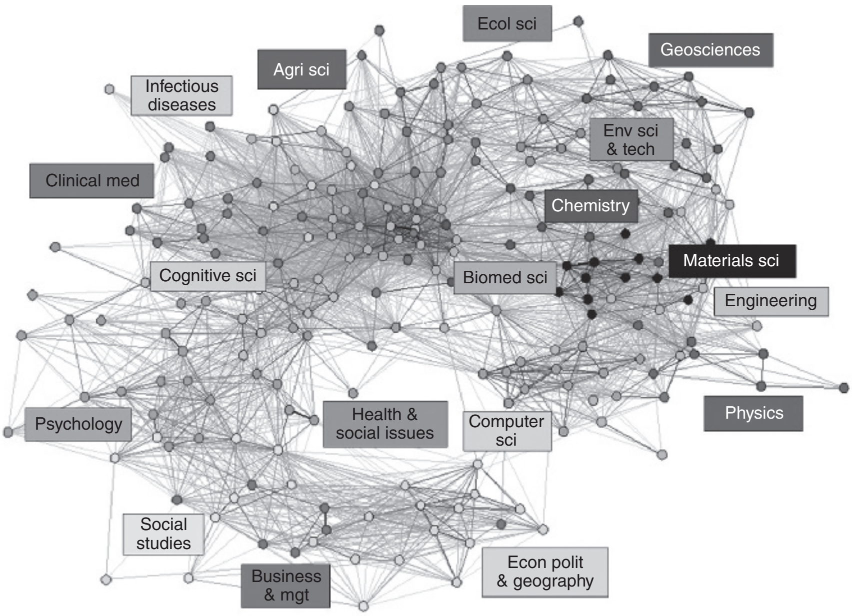


Figure 1.9 Global science map (Rafols et al., 2010).

The fundamental problem with ad hoc collaboration is that it is impromptu, having the character of an improvisation. Often, prospective collaborators know each other or are acquainted through a third party. These relations imply that, by and large, such collaborations do not materialize spontaneously.

Scientific collaboration takes work. First, actively probing for collaborative opportunities and merging skill sets with different researchers takes a lot of work. In addition, authorship issues, project goals mismatch, unclear tasking and responsibilities, different preconceptions about work timeliness (urgency), or—sometimes—incompatible personalities often lead to a failed collaborative effort.

Other problems may arise under a global scientific collaboration regime. Physical distance produces complications. People may be able to meet face-to-face only sometimes. Also, people from different countries operate within various cultures,

7 SPRU: Science and Technology Policy Research, University of Sussex, Brighton, England.

speak diverse languages, and conduct business in different time zones. Finally, global scientific collaboration is hindered due to differences in science funding, customs rules, or security and national regulations issues. These elements are particularly true when collaborating with scientists in less industrialized countries where "professional science" is often in the relatively early stages of progression.

1.3.6 Isomorphism

Systems science claims that all systems, regardless of types and domains, share the same broad principles (depicted in Table 1.2). In other words, systems' characteristics in one domain are *isomorphic* to systems' characteristics in other domains. Isomorphism is a mapping between two sets that define a one-to-one correspondence between the components of each set. Therefore, two isomorphic objects have the same properties and may not be distinguished through their structural attributes.

For example, the two words *poppy* and *daddy* are isomorphic because there exists a linear, one-to-one, and onto transformation[8] (T) between these two words (Figure 1.10).

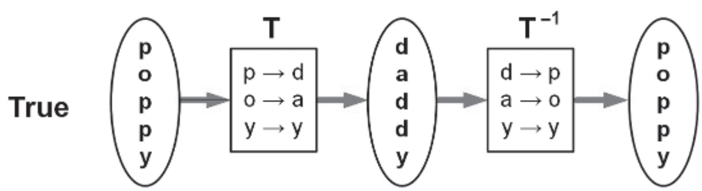


Figure 1.10 Example: two isomorphic words, *poppy* and *daddy*.

On the other hand, the two words *title* and *poppy* are not isomorphic because there exists a linear, one-to-one relationship but not onto transformation (T) between these two words (Figure 1.11).

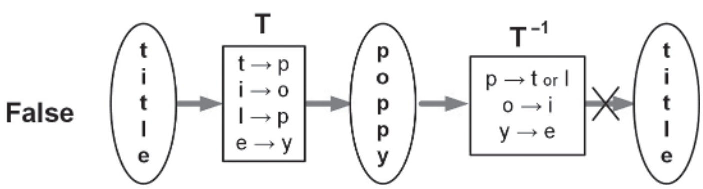


Figure 1.11 Example: two nonisomorphic words, *title* and *poppy*.

8 See more: Bijection. https://en.wikipedia.org/wiki/Bijection. Accessed: Jan. 2023.

A mathematical example of isomorphic objects is depicted in Figure 1.12. Let us transform a fourtuple vector of real numbers (R^4) into a 2×2 matrix of real numbers $M_2(R)$ using the transformation T. This relation is a linear, one-to-one, and onto transformation between the two spaces. Therefore, one can say that R^4 is isomorphic to $M_2(R)$.

$$T\ R^4 \longrightarrow M_2(R) \qquad T\begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \qquad R^4 \cong M_2(R)$$

Figure 1.12 Mathematical isomorphic example.

1.3.7 Overcoming Knowledge Barrier between Domains

Figure 1.13 depicts a general systems science procedure to overcome the knowledge barrier between domains. First, a specific "source" system belonging to a relatively well-known part is analyzed by applying the systems science broad principles described in this figure. The net result of this analysis is a definition of common attributes, properties, and principles of organization and behavior related to the source system. Next, a specific "target" system belonging to a relatively unknown domain is defined based on this information. This definition applies the same methods and broad principles in reverse.

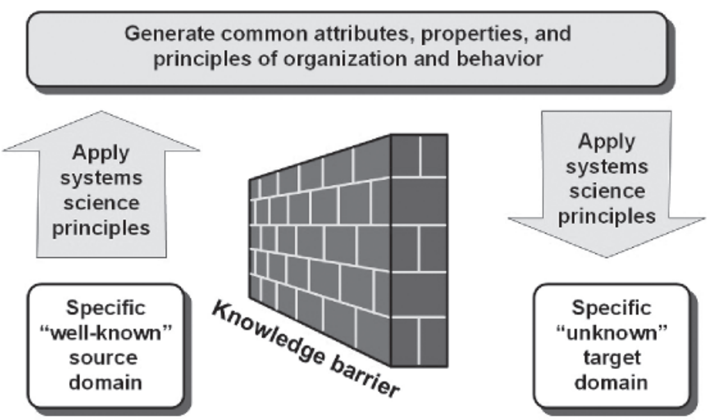


Figure 1.13 A procedure to overcome the knowledge barrier between domains.

1.4 Early Systems Pioneers

Early systems pioneers considered contemporary, twentieth-century science limited by its focus on the discrete parts of reality. They hoped to complement the insulated compartmentalization of the classical science approach with a more holistic approach. In particular, they pursued dialogue, collaboration, and integration between autonomous areas of study. The intent was to model systems' broad behavior and elucidate general principles that can be recognized and applied to other systems in different domains.

Systems science has evolved since the 1950s through many individuals from different natural, social, and formal science disciplines. Two biologists, an economist, a neurophysiologist, a computer scientist, and a mathematical psychologist, all born during the first third of the twentieth century, are widely acknowledged as the founders of systems science.[9] They are discussed in the following sections.

1.4.1 Alexander Aleksandrovich Bogdanov (1873–1928)

Alexander Bogdanov was a Soviet physician, philosopher, science fiction writer, and Bolshevik revolutionary. He proposed unifying all social, biological, and physical sciences, considering them as systems of relationships, and searching the organizational principles that underlie all systems. His pioneering ideas are now regarded as forerunners of systems science theory.

Selected books:

- *Technology Universal Organizational Science/Tektologiya Vseobshchaya Organizatsionnaya Nauka* (Russian), by Alexander Bogdanov, 2003 (revised publication).
- *Bogdanov and His Work: A Guide to the Published and Unpublished Works of Alexander A Bogdanov, 1873–1928*, by John Biggart and Georgii Gloveli, 2017.

1.4.2 Karl Ludwig von Bertalanffy (1901–1972)

Ludwig von Bertalanffy was an Austrian biologist. He grew up in Austria and worked in Vienna, London, Canada, and the United States. He is known as a cofounder of general systems

9 For a comprehansive list of distinguished systems science researchers, see Appendix A.

theory (GST) and the von Bertalanffy growth function, a mathematical model of an organism's growth over time.

Selected books:

- *General System Theory: Foundations, Development, Applications*, by Ludwig Von Bertalanffy, 1969 (revised publication).
- *General System Theory: Foundations, Development, Applications*, by Ludwig von Bertalanffy, Wolfgang Hofkirchner et al., 2015 (revised publication).

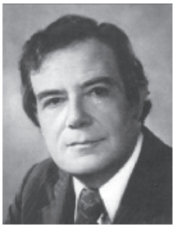
1.4.3 Kenneth Ewart Boulding (1910–1993)

Kenneth Boulding was an English-born American economist, educator, peace activist, and interdisciplinary philosopher. He is also known as a cofounder of general systems theory. Boulding emphasized that human economics and other behavior are embedded in a more extensive interconnected system.

Selected books:

- *The Organizational Revolution: A Study in the Ethics of Economic Organization*, by Kenneth Ewart Boulding, 1953.
- *Conflict and Defense: A General Theory*, by Kenneth Ewart Boulding, 2018 (revised publication).

1.4.4 James Grier Miller (1916–2002)



James Grier Miller was an American biologist, a pioneer of systems science, and an academic administrator. He established the modern use of the term *behavioral science*.

Selected books:

- *Living Systems*, by James Grier Miller, 1978.

1.4.5 Ralph Waldo Gerard (1900–1974)

Ralph Gerard was an American neurophysiologist and behavioral scientist. He is known for his wide-ranging work on the nervous system, nerve metabolism, psycho-pharmacology, and the biological basis of schizophrenia. In addition, Gerard investigated the biology of language, ethics, biology, cultural evolution, education, and the impact of science on public policies.

Selected books:

- *Mirror to Physiology: A Self-Survey of Physiological Science*, by Ralph Waldo Gerard and Wallace O. Fenn, 2012 (revised publication).

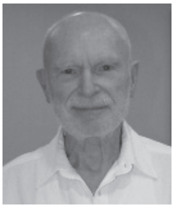
1.4.6 Anatol Rapoport (1911–2007)

Anatol Rapoport was an American mathematical psychologist. He was involved in general systems theory, mathematical biology, and the mathematical modeling of social interaction and stochastic contagion models. In addition, he combined his mathematical expertise with psychological insights to study game theory, social networks, semantics, the psychology of conflict, and international politics.

Selected books:

- *Fights, Games, and Debates*, by Anatol Rapoport, 1974.
- *Decision Theory and Behaviour: Normative and Descriptive Approaches*, by Anatol Rapoport, 1989.
- *Two-Person Game Theory* (Dover Books on Mathematics), by Anatol Rapoport, 1999.

1.4.7 George Jiří Klir (1932–2016)



George Jiri Klir was a Czech American computer scientist and professor of systems sciences at Binghamton University in Binghamton, New York.[10] Klir is known for his research contributions in fuzzy logic, general systems theory, generalized information theory, and interval computations.

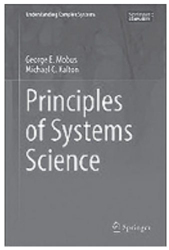
Selected books:

- *An Approach to General Systems Theory*, by George J. Klir, 1969.
- *Fuzzy Sets and Fuzzy Logic: Theory and Applications*, by George J. Klir and Bo Yua, 1995.
- *Facets of Systems Science,* IFSR International Series in Systems Science and Systems Engineering, by George J. Klir, 2001.

10 The author was privileged to study under Professor Klir in the early 1970s.

1.5 Recommended Books on Systems Science

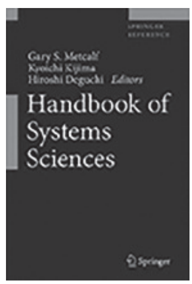
Many scholars[11] at universities and international organizations[12] continue researching within the various systems science arenas. Interested readers are advised to read the comprehensive, integrative, and balanced volume on systems science written by George Mobus and Michael Kalton: *Principles of Systems Science*, which was issued by Springer in 2015.



George Mobus is professor emeritus at the Computing and Software Systems Program, Institute of Technology, at the University of Washington in Tacoma, Washington.

Michael Kalton is professor emeritus of interdisciplinary arts and sciences at the University of Washington in Tacoma, Washington.

Another recommended large and all-inclusive volume on system science, edited by Gary Metcalf, Kyoichi Kijima, and Hiroshi Deguchi, is *Handbook of Systems Sciences*, which was issued by Springer in 2021.



Gary S. Metcalf is a systems theorist and practitioner. He has worked as a family therapist and manager in large corporations. He taught at universities in the United States, Finland, and India for 20 years.

Kyoichi Kijima is a professor emeritus at the Tokyo Institute of Technology; a specially appointed professor at Daito Bunka University; and an adjunct professor at the School of Business Management, Bandung Institute of Technology, Indonesia. He also holds an appointment at the Open University of Japan.

11 See List of systems scientists. https://en.wikipedia.org/wiki/List_of_systems_scientists. Accessed: Jan. 2023.

12 See List of systems sciences organizations. https://en.wikipedia.org/wiki/List_of_systems_sciences_organizations. Accessed: Jan. 2023.

Hiroshi Deguchi is a professor at the Tokyo Institute of Technology, and since 2017, he has been the president of the Japan Association for Social and Economic Systems Studies (JASS).

1.6 Systems Science: Criticisms and Responses[13]

Before proceeding into the rest of the book, readers are invited to examine some criticisms of systems science raised by scientists and laypeople. This section discusses the more relevant ones and responds to them.

1.6.1 Criticisms of Systems Science

Criticisms of systems science are expressed below.

1. **Concepts of systems and models.** Systems science concepts are too general and sometimes too mathematical or too formal. For example, different definitions of *systems* sometimes contradict each other. Also, systems science claims that all aspects of reality are included in its definition of a system. However, this claim leads to the notion that systems science has either an absolute attribute of natural sciences or an absolute attribute of formal sciences. These conflicting attributes make the theory ambiguous.
2. **Structural similarities and integrative concepts**. Systems science aims to identify structural similarities and integrative concepts within different domains. However, empirical studies cannot substantiate this aim, or at least not sufficiently. Conclusions based on analogy could not be considered proof. The use of analogies and the concept of functionalism is not always possible. Also, other interdisciplinary concepts (e.g., open systems, a hierarchy of systems, homeostasis, autopoiesis, control, feedback self-organization, emergence, networks instead of causal chains) are regarded as exaggerated in importance and not belonging exclusively to systems science.
3. **The universal language of science.** Systems science claims to define a universal language of science. Such an objective may be regarded as unattainable. The overwhelming majority of discipline-oriented scientists are made to feel insecure and challenged by such a claim.
4. **Holistic thinking.** Systems science stresses the importance of holistic thinking. This cognitive thinking style focuses on the world, considering its parts as

13 This section was partially adapted, with permission, from Professor Eberhard Umbach's paper (Umbach, 2000).

inseparable from the whole and not existing independently. However, the holistic perspective varies across cultures and genders, and thus it is unscientific and not applicable to the scientific method and empirical testing. In addition, holistic thinking makes it hard to determine cause and effect and can become vague, especially when circumstances become more complex.

5. **Quantification and mathematical modeling.** Occasionally, systems science relies on quantification and mathematical modeling. However, by and large, most real issues cannot be treated sensibly with these instruments. For example, quantification can be limited in pursuing concrete, statistical relationships, leading researchers to overlook broader themes and relationships. Quantification often focuses solely on numbers, and researchers risk missing startling information that may have significant value. Furthermore, quantification provides a distorted sense of objectivity by synthetically separating the observer from the observed.

   Mathematical modeling has many benefits that are pertinent to real-world problems. However, its main disadvantage is often derived from its inaccuracy, which, in turn, emanates from oversimplification of the modeling relative to the actual circumstances. As a result, mathematical modeling results must be interpreted by experts. Of course, different people may interpret the results in different ways.
6. **Unified scientific worldview.**[14] Systems science presents a scientific worldview that is based on holism and reductionism. However, systems science does not have a unified and consistent model of the structure and dynamic of its worldview. As a result, different methodologies are not consistent concerning their worldviews. In addition, a specific worldview is often relevant to individuals in a specific domain or a project but not to others. This confusion results in stakeholders establishing different findings based on different worldviews. For example, one may conclude that humankind is in an environmental crisis due to a lack of widely agreed worldview in human thinking.
7. **Different streams of systems science.** Systems science contends with different streams of science. For example, Hieronymi (2013) identifies five significant streams of science fields: (1) physical systems, (2) living systems, (3) cognitive systems, (4) social systems, and (5) technological systems. Systems science is unable to integrate the different streams within its methodology.

14 Worldview may be defined as a coherent collection of concepts and theorems that allows a person to construct a global image of the world and thus understand their life experience (Derived from Aerts et al., 1994).

8. **Marginalization of basic research.** Systems science researchers are accused of ignoring and marginalizing basic research. Basic research is scientific research with the aim of improving theories to enhance the understanding and prediction of natural phenomena. At the other end of the spectrum, applied research tends to provide near-term solutions for societal shifts toward sustainability in the face of global change.

1.6.2 Responses to Criticism

Responses to the criticisms of systems science are discussed below.

1. **Concepts of systems and models.** The criticism of the excessive generality of the systems concept is not convincing because creating analytical tools that are applicable as generally as possible is part of the overall scientific methodology. Moreover, the systems concept definition is as general as the notion of the numbers system. As in the case of numbers, the generality of using the systems concept cannot be objected to on epistemological grounds. On the contrary, it is desired to be general.

   The critics' claim that systems science ought to decide unequivocally to be either a formal or a natural science is also not convincing. The importance of systems science has to be seen in its function as a network for the specialized disciplines based on the systems concept. In this function, systems science shares the methods of all specialized disciplines of the empirical sciences, formal sciences, and humanities. Depending on the context, the systems concept has to adapt to different demands. In addition, the rules that are valid in the comparative context should hold for systems-oriented works.
2. **Structural similarities and integrative concepts.** Pure analogies have moved somewhat to the background of systems science because conclusions on that basis cannot be regarded as proofs, and the empirical findings of far-reaching "cross-level hypotheses" have encountered severe difficulties, especially when tried without cooperation with specialized disciplines.

   The conclusion must be that interdisciplinary structural similarities belong to the realm of systems science but only in cooperation with the specialized disciplines. General concepts, like emergence or entropy, yield valid statements in a circumscribed field of science. However, they must be accepted by the responsible specialized science. By this token, these concepts are also part of the specialized sciences and thus are not constitutive of systems science.
3. **The universal language of science.** Many systems scientists view this lofty aim as no longer being a task for systems science. In the inevitable and desired interdisciplinary communication, more and more specialized scientists will favor an interdisciplinary precision of their terms without systems science having to be active in this context.

4. **Holistic thinking.** The concept of the top-down approach and the aim of including as many aspects as possible can be regarded as a provisional explication of holistic thinking. Despite all methodological difficulties, a tendency toward holistic thinking is necessary. This tendency is also true in specialized disciplines. The difficulties, especially in the socioeconomic domain, are considerable. When analyzing the results of holistic thinking, the limits have to be indicated, which unfortunately has not been the case in the past. More research into this aspect is necessary.
5. **Quantification and mathematical modeling.** These methods are not constitutive of systems science but instead of science in general. Nevertheless, they have a firm place in systems science methodology and other specialized disciplines. An inadequate quantification methodology cannot be explicitly attributed to systems science.
6. **Unified scientific worldview.** A unified scientific worldview is based on the idea that every scientific component can be tested with empirical observation and conforms to the highest levels of objectivity. However, many scientific ideas cannot be tested adequately. Also, ethics, an inevitable part of a scientific worldview, cannot be tested.

   Another argument related to the quest for a unified scientific worldview is that science has limits. For example, a few things that science does not do are as follows. (1) Science doesn't make moral judgments, (2) science doesn't make aesthetic judgments, (3) science doesn't tell one how to use scientific knowledge, and (4) science doesn't conclude supernatural phenomena.

   In conclusion, some will say that a unified scientific worldview is not attainable. Others will say that creating a unified scientific worldview is not a part of general criticisms of systems science.
7. **Different streams of systems science.** The existence of different streams within systems science is not an exception in the general context of science. There have also been frequent conflicts about streams and approaches in other disciplines. For example, Newtonian theory maintains that objects fall to the earth because their gravitation pulls them. In contrast, Einsteinian theory maintains that objects move freely along curved spacetime trajectories, and the mass and energy of these objects induce these curvatures.
8. **Marginalization of basic research.** Systems science methods define systems and distinguish them from the environment. They also represent, analyze, and optimize their structure and behavior. An agreed-upon classification of systems science disciplines includes (1) general systems theory, (2) cybernetics, (3) operations research, (4) systems analysis, and (5) systems engineering. The first two classes belong to systems theory, and the other three belong to systems applications. As can be seen from

this classification, systems science engagement in basic research is limited. Therefore, this criticism may be justified, but it is not a decisive argument against systems science in general and its epistemological grounds.

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