Chapter Two: Wicked Problems and Their Resolution from Sustainable World:
Approaches to Analyzing and Resolving Wicked Problems by Sonya Remington
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WICKED PROBLEMS AND THEIR RESOLUTION

Core Questions and Key Concepts

Section 2.1: Understanding Wicked Sustainability Problems

Core Question: Why are sustainability problems so difficult to resolve?

Key Concept 2.1.1—Sustainability problems are wicked problems exhibiting six characteristics that make them difficult to resolve using traditional scientific approaches.

Key Concept 2.1.2—Wicked problems are difficult to resolve because they are embedded in socio-ecological systems characterized by complexity.

Section 2.2: Resolving Sustainability Problems

Core Question: How can wicked sustainability problems be resolved?

Key Concept 2.2.1—Current state analysis, future scenarios, visioning, and transition strategies are emerging tools that can be used to resolve wicked sustainability problems.

Key Concept 2.2.2—Weak and strong sustainability represent two different beliefs regarding the extent to which tradeoffs among environment, society, and economy may be made when resolving sustainability problems.

Key Concept 2.2.3—Including a diversity of stakeholders is key to resolving sustainability problems, as it ensures that both local and expert knowledge are incorporated into problem-solving processes and that solutions have "staying power."

Key Terms

wicked problem	system	boundary
tame problems	component	open system
complex system	interaction	closed system
norm	simple system	reductionist thinking

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Key Terms (*Continued*)

holistic thinking
cascading effects
scale
dynamics
stock (aka. reservoir)
flow
albedo
inertia
Transformational Sustainability Research (TSR)
current state analysis
indicator
scenario
vision
visioning
tradeoff
weak sustainability
strong sustainability
participatory approach
co-production
transdisciplinary

"A wicked problem is a complex issue that defies complete definition, for which there can be no final solution, since any resolution generates further issues, and where solutions are not true or false or good or bad, but the best that can be done at the time. Such problems are not morally wicked, but diabolical in that they resist all the usual attempts to resolve them."

—Tackling Wicked Problems Through the Transdisciplinary Imagination

Section 2.1: Understanding Wicked Sustainability Problems

Core Question: Why are sustainability problems so difficult to resolve?

wicked problem a difficult problem that cannot be addressed using only traditional approaches, such as scientific and technological advances, and that requires continuous attention because it can never be completely resolved.

tame problem a relatively simple problem that can be solved using traditional approaches, such as scientific and technological advances.

Sustainability challenges are commonly referred to as **wicked problems**. As illustrated in the opening quote to this chapter, this is not because they are morally bad or wicked as opposed to morally good. It is because they are very complicated and seem to withstand traditional approaches to solving them. Traditional approaches refer to the scientific and technological advances that have solved many of society's problems in the past. These traditional approaches can solve **tame problems**. For example, the development of vaccines to prevent diseases such as smallpox, polio, typhus, and tetanus have greatly improved human health. The solution to these human health issues was arrived at using the scientific method. In these cases, everyone agreed disease was a problem that should be solved. The problem was thoroughly analyzed and adequately understood prior to developing solutions. The

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solution to the problem (a vaccine) was arrived at and mutually agreed upon through the traditional process of the science. Once the problem was solved, that was the end of the story.

Problems are tame problems when approaches to solving them involve moving from problem to solution in a step-by-step, linear fashion and relatively straightforward manner. It is clear when the problem is solved and there is nothing left to do. Other examples of tame problems include calculating the square root of 5234, finding the shortest route from your home to your workplace using a map, repairing a car, or putting a man on the moon. An important point here is that a tame problem is not necessarily simple. In fact, especially in the case of putting a man on the moon, it can be incredibly technically complex. Thus, a major distinguishing feature between tame and wicked problems is not that tame problems are simple. Rather, it is that wicked problems are embedded in **complex systems**. Such systems have certain features such as high interconnectedness, cascading effects through multiple spatial and temporal scales resulting in unintended consequences, large uncertainties due to nonlinearities, path dependence, and inertia, and self-regulation due to feedbacks. The chapter will begin by describing six general characteristic that define wicked problems and then explain how features of complex systems render wicked sustainability problems so difficult to resolve.

complex system a system in which the many parts that compose the system are interconnected in an irreducible way, such that the whole system is greater than the sum of the parts.

Section 2.1.1—Introduction to Wicked Problems

Key Concept 2.1.1—Sustainability problems are wicked problems exhibiting six characteristics that make them difficult to solve using traditional scientific approaches.

The term *wicked problem* was first mentioned in the 1970s urban planning literature in a famous article written by University of California, Berkeley professors Horst Rittel and Melvin Webber. They describe 10 characteristics of a wicked problem, but for the sake of simplicity, six general characteristics are given here:

1. Vague problem definition
2. Undefined solution
3. No endpoint
4. Irreversible
5. Unique
6. Urgent

This section will first describe these characteristics and illustrate their application using a hypothetical climate change example (**Box 2.1**). Then, the section will conclude by briefly comparing tame problems with wicked problems

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using the six characteristics in order to solidify the difference between these two types of problems.

Characteristic 1: Vague Problem Definition. Wicked problems have a *vague problem definition*. This is because there are multiple and diverse stakeholders involved. Diversity among stakeholders is the result of many specific factors including living in different geographic locations, under different governance regimes with different capacities to deal with problems, and in societies with different cultures, values, beliefs, and informal **norms**. Diversity among stakeholders also means that not everyone will agree on the extent to which some issue is a problem or if it is even a problem at all. These ideas are illustrated with Characteristic 1 in the hypothetical example of global climate change as a wicked problem (Box 2.1).

norm defines what is approved or disapproved of within a society and, as a result, tends to shape or guide people's actions.

BOX 2.1 CONCEPT ILLUSTRATION

Note: Although this example is mostly hypothetical and meant for illustrative purposes only, the cities and states mentioned are real places. In addition, the citizens of Kivalina, Alaska, did attempt to sue 24 oil, energy, and utility companies that they accused of causing climate change.

Characteristic 1: Vague Problem Definition. Stakeholders from two different geographical locations illustrate why a wicked problem such as climate change is vaguely defined. One stakeholder groups is composed of the 400 residents of a small coastal Inupiat Eskimo village called Kivalina, which is located on a peninsula of land in Alaska that protrudes into the Chukchi Sea. The residents of this village may have to relocate soon at a total cost of $95 to 400 million. Global climate change has caused warming in this region and melted Artic sea ice. Previously, this sea ice protected Kivalina from violent winter storms in the same way that a human-engineered levee or seawall protects coastal communities. Now that there is less sea ice, there has been increased erosion and destruction of properties on the island during storms. Eventually, the island will be underwater. To the people of Kivalina, climate change is a problem that urgently needs to be addressed and they have gone so far as to sue 24 oil, energy, and utility companies that they accuse of causing climate change.

Stakeholders in the San Francisco Bay Area (SFBA), in the other hand, defined the problem differently. The SFBA is a large metropolitan region approaching a population of 8 million people. The topography is very hilly and winter storms are mild. As a result, most people in this region do not feel the immediate effects of climate change induced sea level rise. Based on geographical location alone, the majority of Kivalina residents would say that climate change is an urgent problem that needs solving. Those living in San Francisco might not see climate change as a problem and those who do might not view this problem as urgent. Climate change is a global problem involving all people around the world. Only three stakeholders groups were identified here: Kivalina residents, energy companies, and San Franciscans. The countless stakeholder groups involved in the issue of climate change, due to its global nature, make this an especially wicked problem.

Characteristic 2: Undefined Solution. Suppose that both Kivalina and SFBA residents agree that climate change is an urgent problem that needs immediate attention. Their consensus about problem definition does not mean they will agree on a solution. The residents of Kivalina propose nuclear energy as a technological solution. They claim that the SFBA has a much larger population than their small village and, therefore, contributes much more climate change causing CO_2 to the atmosphere. Based on this, the Kivalina residents argue that the SFBA should take action to mitigate climate change. They propose that the SFBA build a nuclear reactor in its region to provide electricity to its large metropolitan area. The residents of the SFBA object to this because they don't want a nuclear power plant in their backyard, especially in light of the recent earthquake-related nuclear disaster in Fukushima, Japan. The SFBA is also at risk of an earthquake along the San Andreas Fault. Instead, the residents of the SFBA propose a huge national gas tax of 0.85 per dollar spent on gasoline as an economic disincentive to people using gasoline-powered forms of transportation. Burning gasoline in cars and other forms of transportation contributes large amounts of CO_2 to the atmosphere. The SFBA has invested in electric streetcars and a network of bike paths. Therefore, a nationwide gas tax would not significantly affect people in the region because they can use alternative forms of transportation. The residents of Kivalina are completely dependent on gasoline-powered automobiles and motorboats to move within and around the island. They are opposed to the gas tax and insist on the SFBA nuclear power plant. Even in this simple case of only two stakeholders, there is an *undefined solution* to the wicked problem of climate change. One proposed solution is technical and the other economic.

Characteristic 3: No End Point. Pretend that the residents of Kivalina and the SFBA both agree that the solution should be a nuclear power plant in the SFBA. There may be several further problems generated once the solution is implemented. For example, the financial burden on the SFBA may increase due to the need for increased security measures. The SFBA is home to an international airport and a very large human population where troublemakers can easily get lost in the crowd. To protect against terrorist plots to blow up the nuclear power plant, the city might have to invest in expensive infrastructure and hire a large team of security specialists. Once this is done, is the problem solved? Do we stop here? Probably not. Another issue that may arise is that, due to new high security measures and the associated hassle, many residents may no longer want to live in the city and choose to move away. Tourists may choose to vacation elsewhere. Both of these things would take income away from the city and decrease its wealth, which would reduce its capacity to support increased security measures and also to deal with environmental cleanup of leakages of nuclear waste from the plant were that to occur as conditions change into the future. What solution can be implemented at that point or should they just stop there?

Characteristic 4: Irreversible. If a nuclear power plant were established in the SFBA, radioactive chemicals such as uranium or plutonium would be brought into the region. The nuclear fission reactions that drive electricity generation in a nuclear power plant create radioactive chemical waste that requires tens of thousands of years to decay to safe radiation levels. This waste will need to be stored somewhere, and leakage from underground storage tanks is not uncommon.

(continued)

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Thus, implementing the nuclear energy solution to climate change will result in irreversible consequences that will impact many people in the future.

Characteristic 5: Unique. What if a nuclear power plant were installed in Kivalina instead of the SFBA? Although the same solution can be implemented, the outcome may be very different. Building a nuclear power plant to provide electricity for 400 people is not practical, and transporting this electricity to other places would be resource intensive. Also, hundreds of people are permanently employed at nuclear power plants, and it takes thousands of people to construct one initially, so Kivalina would need to attract employees from other parts of the world. This could prove expensive and impractical due to its remote geographic location.

Characteristic 6: Urgent. In the case of Kivalina, climate change could eventually lead to sea level rise that covers the entire island. This could lead to many permanent harms to people, such as loss of homes and livelihoods, economic burdens for relocation as climate refugees, and in the most extreme cases death due to increasingly large storm surges. The same holds for ecosystems. In addition to climate change and sea level rise, increased levels of CO_2 in the atmosphere have resulted in acidification of ocean waters. Continued ocean acidification could lead to damaged reef and tidal ecosystems and in the worst case permanent extinction of certain species in these ecosystems. Climate change, with all its associated uncertainties and conflicting interests involved is a great example of an urgent problem that needs immediate attention before the problem is fully understood.

Characteristic 2: Undefined Solution. The second characteristic of a wicked problem is that there is an *undefined solution*. In other words, there is no one definite solution to the problem; also, multiple and diverse stakeholders are involved. Even if there is consensus on the problem definition, not everyone will agree on when the problem has been resolved and how effectively. This point is illustrated under Characteristic 2 in Box 2.1.

Whether a solution to a wicked problem is "the right one" or "the wrong one" depends on who you ask. This can be contrasted with a tame problem, such as finding the square root of 256. No matter whom you ask, the correct solution to this problem is 16. The solution is objective. Solutions to wicked problems are subjective. They are not black and white in an absolutely right or wrong sense like a math problem, but rather cover different shades of gray in that some are better or worse than others or are good enough or not good enough relative to a specific situation and the resources available to work on solving the problem. A solution that is good enough for one place and time might be not good enough for another.

Characteristic 3: No End Point. The third general characteristic of a wicked problem is that there is *no end point*. When a solution is implemented, new problems arise because wicked problems are embedded in interconnected and complex systems, which makes them prone to cascading

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effects and unintended consequences (ideas presented in the next section, Section 2.1.2). Also, conditions change through time, and solutions must be continually adapted to meet new conditions. As a result, there is no obvious point at which we should cease trying to solve the problem. There are no final solutions to wicked problems. Rather, it is an ongoing process. As a result, the word *resolving* rather than *solving* is used in this textbook to refer to attempts at addressing wicked problems. Although they are often used interchangeable, in this textbook the former meaning is intended.

In reality, the implementation of new solutions often stops when the resources needed to solve a problem, such as money, time, and energy, become scare. Even when the problem-solving process has stopped due to resource constraints, problems remain and new ones continue to arise. Thus, when devising and implementing solutions to wicked problems, it is important to try to anticipate new future problems to be prepared for as they arise through time.

Characteristic 4: Irreversible. The fourth characteristic of a wicked problem is that it is *irreversible*. This means that the effectiveness of a solution cannot be verified prior to implementation through low-stakes trial-and-error testing like in a science experiment. Implementing a solution creates changes in the world that cannot be undone and will have real consequences.

Characteristic 5: Unique. The fifth characteristic of a wicked problem is that it is *unique*. This means that the same solution will not work effectively in all places. Every specific situation is distinct because the cultural, political, social, environmental, technological, economic, and other important aspects will be different in particular contexts.

Characteristic 6: Urgent. The sixth and final characteristic of wicked problems is that they are *urgent*. These problems are urgent because a failure to act will result in permanent harm to human and natural systems. The urgency of wicked problems presents challenges for resolving them. Because these problems are so urgent, solutions must often be pursued prior to a full understanding of the problem. Given this, in addition to the fact that financial and other resources required for problem solving are limited, convincing key stakeholders to use their resources to take actions toward pursuing solutions without full information can be extremely difficulty. It is because of these challenges that sustainability problem solvers warn of "paralysis by analysis," cautioning against too much problem analysis before action is taken.

Wicked Problem-Tame Problem Comparison. In summary, wicked problems cannot be solved using methods traditionally used to solve many problems for human societies. To solidify how wicked problems differ from tame problems, the characteristics of a wicked problem will be applied to the vaccine example (a tame problem) with which this section was opened. Wicked problems have *vague problem definitions* because there are multiple and diverse stakeholders. The smallpox disease is a tame problem because most stakeholders would agree that it is horrible disease that should be cured. Thus, smallpox is a clearly defined problem.

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Wicked problems have *undefined solutions*. The technical solution to the smallpox problem was to develop a vaccine. Once a person acquired the smallpox virus, there was no cure so the only solution was prevention. In Medieval England, before the smallpox vaccine was developed, people used to think that hanging red curtains around the patient's bed would cure the disease. However, this did not work. Even if someone preferred this solution to a vaccine, perhaps because they thought red curtains were decorative, it would be clear in the end that red curtains do not work. There is a defined solution to tame problems.

Wicked problems have *no end point*. Once the smallpox vaccine is developed, there is an obvious point where we cease problem solving in the medical research laboratory where the vaccine was developed. Although a small number of people may have complications from the vaccine, which would be considered an unintended consequence, overall it is a successful solution to the problem of smallpox and further efforts to produce solutions to the problem are not needed.

Wicked problems are *irreversible*. A scientist working in a laboratory to develop a smallpox vaccine learns by trial and error. This does not have real consequences for society as a whole. If one vaccine does not work, the scientist can try another one without much of a penalty for making a mistake.

Wicked problems are *unique* and require context-specific solutions. However, the smallpox vaccine is not a unique solution because the same solution to this disease works effectively in places around the world. Basic laws of physics, chemistry, and biology make this so. On the other hand, the socio-ecological systems in which wicked problems develop are not completely governed by such universal principles and local context is an important factor to consider when devising solutions.

Finally, wicked problems are *urgent*. They require that action be taken toward solutions prior to a thorough understanding of the problem. This is not to say that the polio epidemic was not urgent, but the problem could be sufficiently identified and analyzed before proposing solutions.

Section 2.1.2—Wicked Problems, Socio-ecological Systems, and Complexity

Key Concept 2.1.2—Wicked problems are difficult to resolve because they are embedded in socio-ecological systems characterized by complexity.

> *"Just how complex is a particular system? Is there any way to say precisely how much more complex one system is than another? . . . Is a human brain more complex than an ant brain? Is the human genome more complex than the genome for yeast? Did complexity in biological organisms increase over the last four billion years of evolution? . . . These are key*

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questions, but they have not yet been answered to anyone's satisfaction and remain the source of many scientific arguments. [N]either a single science of complexity nor a single complexity theory exists yet . . . [R]ather [there are] several different sciences of complexity with different notions of what complexity means. . . . Intuitively, the answer to these questions would seem to be "of course." However, it has been surprisingly difficult to come up with a universally accepted definition of complexity that can help answer these kinds of questions."

—Melanie Mitchell, Complexity: A Guided Tour, 2009

The major reason that wicked problems are so difficult to resolve is that they are embedded in socio-ecological systems that exhibit complexity. Thus, resolving them requires an understanding of their complexity. All systems, a car or an ecosystem or an economy, are made up of individual components and interactions among those components. Thus, this section will start by defining what is meant by a system, any system. However, the degree of complexity exhibited by different types of systems is not always the same, and defining how complexity differs among various systems is not straightforward. As implied in the opening quote to this section, precisely articulating just how complex some systems are relative to others is a very active area of research. As such, this section will introduce a set of tools for thinking about complexity rather than a comprehensive set of hard-and-fast rules that define complexity because the latter simply does not yet exist.

The tools for thinking about complexity presented here, and in much more detail in later chapters (especially Chapters 5 and 6), can be considered as part of a "toolbox." When confronted with a repair, such as fixing a leaky kitchen sink drain pipe connection, you might need a pipe wrench and slip joint pliers, but you will not likely need a screw driver or a handheld circular saw. Similarly, you will not necessarily need all the tools for thinking about complexity presented in this textbook for understanding and resolving wicked problems in every single SES that you focus on. However, it is good to have all of these tools at your disposal in case you do need them in some cases. The tools are derived from ideas, theories, and frameworks for thinking about the world used and developed in several fields that consider complexity as part of system analysis. These include dynamical systems theory, economics, thermodynamics, information theory, computation, evolutionary biology, ecology, and many others. The interested reader should consult the excellent book by Melanie Mitchell (*Complexity: A Guided Tour*) for a more detailed look at how different fields of study that have shaped thinking about complexity.

For the purposes of this introductory sustainability textbook, the tools for thinking about complexity will be focused on those that build an initial and general understanding of SES behavior. Because there is no universally accepted definition of complexity, terms are clearly defined as having a

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specific meaning in this textbook and may differ from how they are defined elsewhere. This is not to say that other definitions are "wrong" or inaccurate by any means, but our definitions are provided merely to ensure a coherent presentation of the concepts introduced in this textbook. The systems outlook necessary for comprehending SES behavior must holistically incorporate the relatively well-characterized processes relevant to both human and natural systems as well as accommodate historical legacies and a wide range of indeterminate human actions. To meet these conditions, with specific attention to sustainability, tools for thinking about SESs have been drawn from several sources:

- Basic systems thinking concepts derived from systems modeling (e.g., *Thinking in Systems: A Primer*, 2008, Donella Meadows)
- Dynamical systems theory as applied to natural and human systems to understand patterns of change (e.g., *Critical Transitions in Nature and Society*, 2009, Martin Scheffer)
- Reliance approaches to understanding and managing complex adaptive systems (e.g., *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*, 2006, Brian Walker and David Salt; *Human Ecology: Basic Concepts for Sustainable Development*, 2001, Gerald G. Marten; *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World,* 2009, edited by F. Stuart Chapin III, Gary P. Kofinas, and Carl Folke)
- Adaptive cycles framework for thinking about long-term change and resilience in evolving systems (*Panarchy: Understanding Transformations in Human and Natural Systems*, 2002, Lance H. Gunderson and C.S. Holling; *Human Ecology: Basic Concepts for Sustainable Development*, 2001, Gerald G. Marten)

This textbook will only scratch the surface of the ideas presented in many of these books and the interested reader should consult them if more in-depth knowledge is desired.

Socio-ecological Systems. The wicked problems described in the previous section are difficult to resolve because they are embedded in SESs that exhibit varying degrees of complexity. Before delving into tools for thinking about complexity, a more precise understanding of what is meant by an SES and why they are needed to understanding wicked problems must be presented. For a long time, humans studied natural systems as outside observers figuring out how to fix problems such as environment degradation. However, this removes humans from the system, whereas, in reality, humans and their actions are integral parts of the systems from which wicked problems arise. As described in Chapter 1, human societies have always influenced, and been influenced by, natural systems. Many of the problems facing natural systems today are rooted in human systems and the opposite can also be true (such as with natural disasters). The goal of sustainability is to simultaneously promote healthy ecosystems, human well-being, and viable economies. All of

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this means that human and natural systems must be studied together rather than separately, as socio-ecological systems (SESs, also known as coupled human-environmental systems).

The SES framework for solving sustainability problems represents the dynamic, two-way interaction between human and natural systems (**Figure 2.2**). Humans interact with natural systems in order to gain some useful resource from them and take advantage of ecosystem services. As a result, they impact the natural system in some way through human activities. If the impact is severe enough, it can reduce the capacity of natural systems to provide human systems with the resources and ecosystem services needed for survival. When human systems become aware of this impact, people and institutions take action or make changes in response. This action also impacts human systems. The two-way interaction between human and natural systems continues in this way indefinitely. These ideas are illustrated with an example of changes in agricultural systems during the Industrial Revolution (**Box 2.2**).

Do SESs really exhibit that much complexity? After all, the example given in Box 2.2 seems relatively straightforward. However, SESs can exhibit certain behaviors that make them incredibly difficult to understand and manage. These features arise from the *dynamic network of interactions among system components* and the *ability of systems to continually adapt to changing external conditions*. There is a great deal of meaning behind many

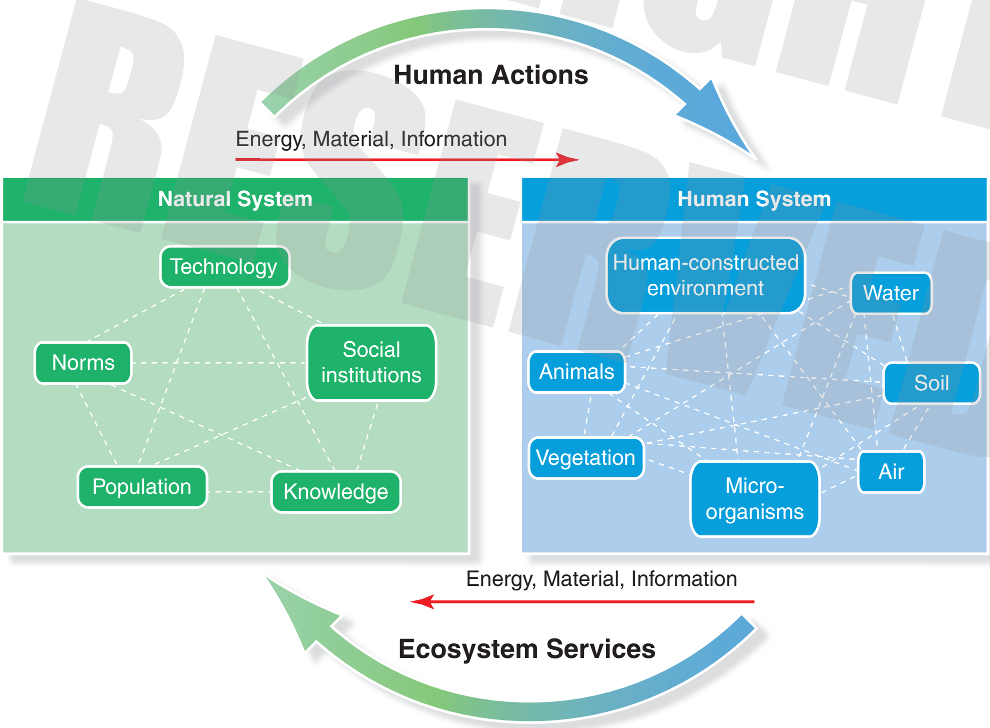

Figure 2.1

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BOX 2.2 CONCEPT ILLUSTRATION

In an agricultural system, people grow crops such as corn in order to have food to eat. During the Industrial Revolution, in an effort to increase the amount of food produced for a growing human populations, agriculture became mechanized such that fossil-fuel-powered tractors and other equipment replaced human labor. However, there were unintended consequences to this action in terms of impacts on natural systems. The fossil fuels used to power tractors added excess CO_2 to the atmosphere and this affected the climate. The tractor allowed vast areas of land to be plowed, which were often left fallow after a crop was harvested. The bare soil on this land was more susceptible to erosion by wind and water than soil covered with a crop. The stability of climate and the health of soils both impact the capacity of a plot of land to support crops. If this capacity decreased, less food would be available for people to eat, and human well-being would be negatively impacted. This new information about the natural system was transmitted to the human system. People working in environmental nongovernmental organizations (NGOs) noticed the impacts of mechanized agriculture on soils and climate. The NGOs directly lobbied the government to put in place policies to protect soils and climate. They also raised awareness with citizens, who also lobbied the government. Governments worked with farmers to develop a plan to reduce soil erosion, such as the use of cover crops. Next, the use of synthetic nitrogen fertilizer arose as another technological advance for agriculture. However, fertilizer use results in excess N_2O gas, which affects climate. Climate change causes severe drought in some regions and flooding in others, which both decrease food production. New information about the natural system again feeds back to the human system and the process of response by the human system starts all over again.

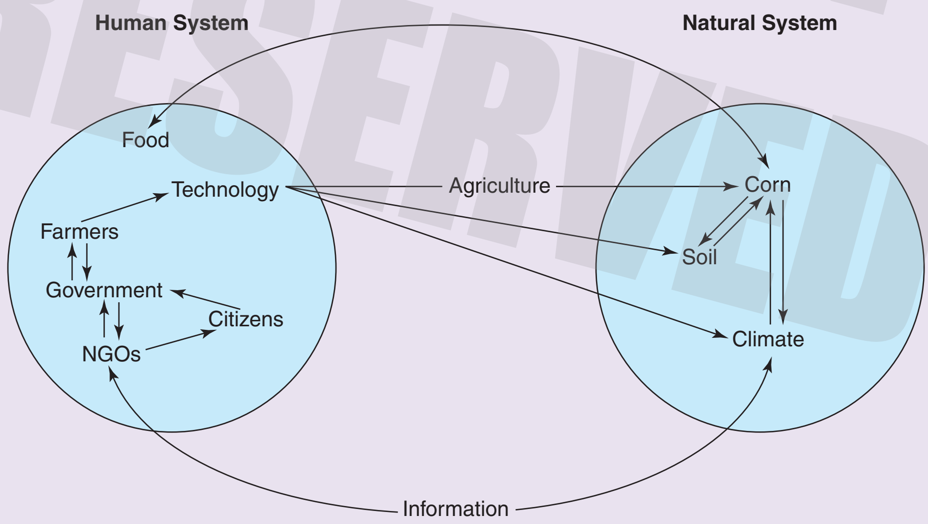

Figure 2.2

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of the italicized words in the previous sentence. Precise definitions of some of these words are given in the remainder of this section, while others are merely introduced an in-depth descriptions left for later chapters of this textbook (especially Chapters 5 and 6). Three types of systems are defined in the remainder of this section to characterize different levels of complexity: simple systems, complex systems, and complex adaptive systems. All three types have implications for understanding SESs and resolving the wicked problems embedded in them.

Complexity Level 1: Simple Systems. Regardless of the level of complexity that they exhibit, all **systems** consist of a set of interconnected components structured in such a way that the interactions among the components accomplish some purpose that cannot be achieved by any of the components alone. **Components** are the different parts of a system, such as a steering wheel in a car system, trees in an ecosystem, the stomach in the digestive system, consumers in an economic system, and elected officials in a political system. **Interactions** are the processes through which different system components associate with each other, such as a steering wheel interacts with a gear through physical forces to turn the car, trees interact with CO_2 in the air through photosynthesis, or a consumer interacts with a producer through purchasing in an economic system. In these systems, the steering wheel and gears, trees and CO_2, and consumers and producers are all components, whereas physical forces, photosynthesis, and purchasing are the interactions between components.

The purpose accomplished by each of these systems—steering a car, turning CO_2 into food using sunlight energy, exchanging goods and services—cannot be achieved by any of the individual components alone. This is an important point because not all collections of random things are systems, such as rocks lying on a sidewalk, because they are not interacting in a way the achieves some purpose that none can accomplish alone. If one or two rocks are taken away, they are still just a bunch of rocks lying on the sidewalk. However, if the gears were removed from a car, the trees removed from a forest, or the consumers removed from an economy, then these systems would no longer accomplish the same purpose.

A bicycle is an example of a **simple system** made up of many components and interactions among those components. Some components of the system that collectively serve the purpose of moving the bike forward include the pedals, crank arm, chain ring, chain, cog set, and front and rear wheels (**Figure 2.3**) Interactions among these components that move the bike forward are different physical forces exerted among the components. The person riding the bike uses force to push down on the pedals, and this causes the crank arm to rotate the chain rings. The chain rings move the chain, which is connected to the cogset on the back wheel. The movement of the chain causes the cogset to rotate, which results in the rear wheel turning and the bike moving forward.

In addition to components and interactions, all systems have **boundaries** that separate the internal components and interactions from the external

system a set of components and the interactions among them that function together as a whole to accomplish or serve some purpose.

Component a single element in a system that plays a specific role as part of the overall system.

Interaction a process through which a subset of system components relate to each other.

simple system a system in which components interact with each other to serve some purpose, but are not connected in an irreducible way as in a complex system.

boundary an imaginary line drawn around a system to conceptually separate the internal components and interactions from the environment external to the system.

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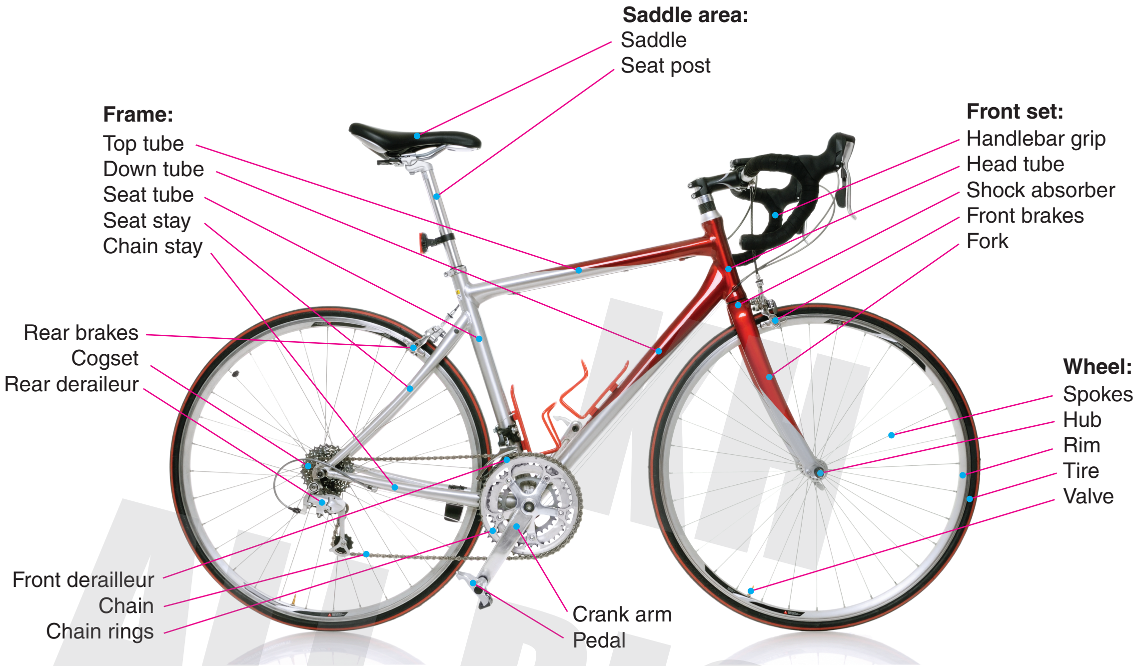

Figure 2.3

environment. Boundaries can be real, such as a chicken wire fence surrounding a garden system to keep out cats who like to use it as a litter box, or imaginary. It is the imaginary boundaries that are of more concern to understanding the ideas presented in this textbook. Imaginary boundaries are lines drawn around a system to mentally separate it from the external environment that influences a system's behavior to varying degrees. All systems considered in this textbook are **open systems** such that energy, materials, and information move across system boundaries from the external environment into the system or vice versa. As a result, the processes occurring outside of a system's boundaries can affect the system and cannot be ignored just because they are outside of the boundaries. This is opposed to **closed systems**, which do not interact with their external environments. In open systems, external processes are often important to fully understanding system behavior.

open system a system in which energy, materials, and information can move freely across system boundaries from the external environment into the system and vice versa.

closed system a system in which energy, materials, and information cannot move across system boundaries from the external environment into the system nor vice versa.

If the external environment can influence a system's behavior, then why bother separating a system from its external environment using boundaries in the first place? Boundaries are defined to simplify real-world systems, which contain seemingly limitless numbers of components and interactions among those components. As such, boundaries are delineated to include those components and interactions most important to understanding the problem being addressed. There is no one valid boundary for any given system, and boundaries vary not only as a result of the problem being addressed, but also for the same problem and system based on the perspective of the person defining the boundary. This is especially important for SESs, which are studied by a wide range of natural and social scientists and also incorporate practical knowledge (see Section 2.2.3). Ecologists, economists, anthropologists, and

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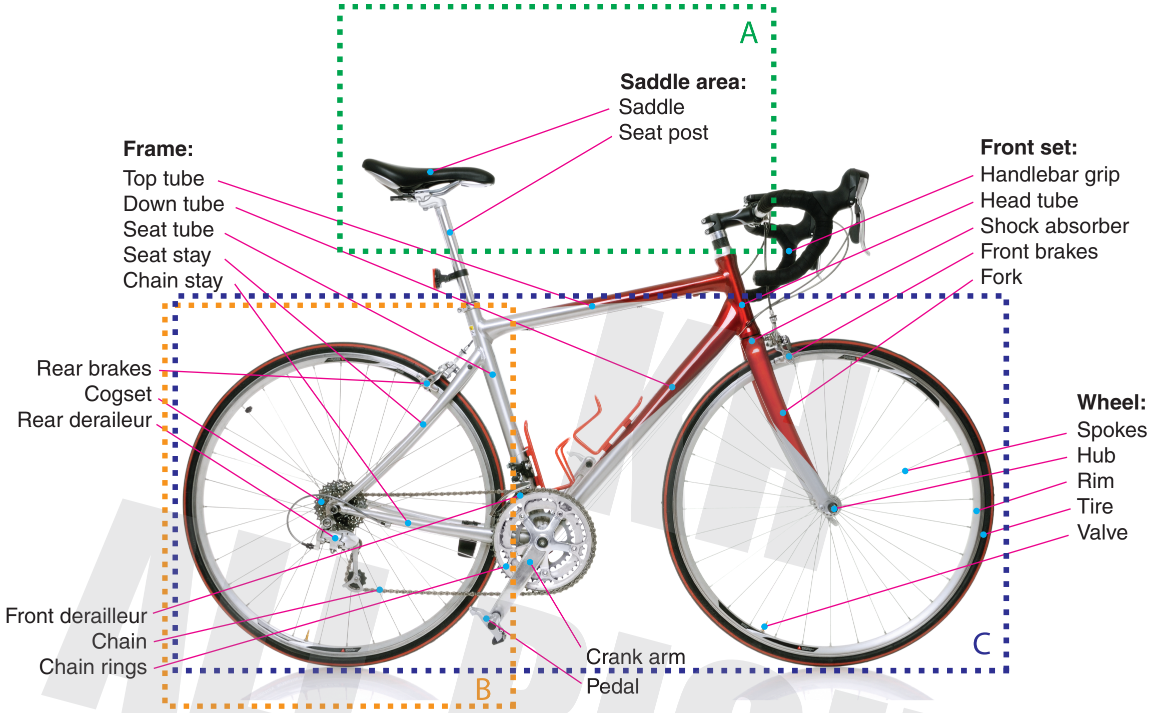

Figure 2.4

practitioners might all draw different boundaries around the same system to address the same problem based on how their diverse perspectives shape their understanding about how the world works. They might also choose to include different components and interactions for the same reasons. But we are getting ahead of ourselves here.

For now, the simple system bike example is used to illustrate how the problem being addressed determines how system boundaries are defined. Pretend that your bike will not move forward. What components and interactions will you need to include in your system to understand this problem? **Figure 2.4** shows three possible system boundaries A, B, and C. The boundaries are portrayed with dotted lines, rather than solid lines, to indicate that they are open systems influenced by processes in the external environment. If you suspect that a flat in your rear tire is the reason that your bike will not move forward, then you could define the system boundary to be Boundary B. If you suspect that a broken chain is the problem, then you would need to broaden your boundary to Boundary C. Defining your system boundary to be Boundary A is unlikely to help you understand why your bike will not move forward. Formally defining system components, interactions, and boundaries in this way in order to understand the bike system and solve the problem of your bike not moving forward may seem unnecessary and excessive for this simple system. Although simple systems such as a bike or even a spacecraft meant for travel to other planets can be complicated, these systems are not considered complex. However, ecosystems, economies, and political systems are complex systems and the tools for thinking about complexity presented

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thus far are important for understanding and resolving wicked problems in SESs, which exhibit much greater complexity. Before moving on to tools for thinking about complexity beyond simple systems, three important ideas relevant to understanding SESs that build on the tools presented in this section will be described: the importance of holistic thinking, the potential for cascading effects, and the multi-scalar nature of SESs.

Holistic Thinking. The components are SESs are highly interconnected through their interactions to accomplish some purpose that cannot be achieved by any of the components alone. Therefore, it is best to look at the system as a whole when trying to resolve a problem and not just a single component. **Reductionist thinking** has dominated knowledge production for centuries, as traditional disciplines were further divided into more and more specialized areas of study. For example, the discipline of biology was broken into many different areas of study such as genetics, molecular biology, physiology, ecology, and many others. This specialization allowed for many discoveries that contribute to human well-being and is still necessary for solving many problems, but a more integrated way of looking at the world through **holistic thinking** is necessary to ensure the sustainability of SESs into the future. This is analogous to the need to view the bike system as a whole, rather than its individual components, when figure out why the system as a whole will not move forward. The importance of holistic thinking to resolving wicked problems can be illustrated with the story of the *Blind Men and the Elephant*:

Reductionist thinking
a point of view that claims systems can be understood by studying each individual component and the interactions among those components as separate from the overall system.

holistic thinking
a point of view that claims systems *cannot* be understood by studying each individual component and the interactions among those components in isolation from the overall system.

> *Beyond Ghor, there was a city. All its inhabitants were blind. A king with his entourage arrived nearby; he brought his army and camped in the desert. He had a mighty elephant, which he used to increase the people's awe. The populace became anxious to see the elephant, and some sightless from among this blind community ran like fools to find it. As they did not even know the form or shape of the elephant, they groped sightlessly, gathering information by touching some part of it. Each thought that he knew something, because he could feel a part. . . . The man whose hand had reached an ear . . . said: "It is a large, rough thing, wide and broad, like a rug." And the one who had felt the trunk said: "I have the real facts about it. It is like a straight and hollow pipe, awful and destructive." The one who had felts its feet and legs said: "It is mighty and firm, like a pillar." Each had felt one part out of many. Each had perceived it wrongly. . . . This ancient Sufi story was told to teach a simple lesson but one that we often ignore: The behavior of a system cannot be known just by knowing the elements of which the system is made.*
>
> *—Thinking in Systems by Donella H. Meadows (p. 7)*

By viewing the world in a reductionist manner, we are like the blind men trying to resolve sustainability problems. We do not see the system holistically; we only see specific components of the system. As a result, conclusions about the behavior of a system can be wrong and unexpected behaviors

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(*surprises*) are more likely when system components are viewed in isolation. Another example can be seen in the human body. High blood pressure causes the heart to work harder to pump blood; this can lead to a heart attack. High blood pressure can be caused by many things including diet, lifestyle choices such as smoking or lack of exercise, obesity, stress, genetics, age, thyroid disorders, or kidney disease. In order to resolve this problem the circulatory system, which is what the disease impacts, cannot be considered in isolation from other components. One must look outside the circulatory system to the urinary system (kidneys), immune system (thyroid), and beyond to the food that a person eats, overall lifestyle, and even genetic makeup.

Acknowledging the interconnectedness among SES components and the need to view them holistically is particularly important at this juncture in human history. For the first time ever, we live together in an intimately linked global society. Just like a problem in one part of the body can cause a heart attack in another part that can lead to death, a problem in one part of the world can have impacts on many other parts of the world the can lead to suffering. This idea is illustrated with a global food crisis case study in **Box 2.3**.

A final point to make about interconnectedness of SESs is that there is no simple, singular solution to wicked problems. Instead, several solutions must be pursued simultaneously. This idea can be illustrated by drawing from an article on global food security written for the journal *Science* in 2010 by British biologist H. Charles Godfray and his colleagues. In this article, three challenges to the future of food security are presented: increasing wealth around the world for some will increase demand for meat and other energy intensive foods (the A in the I=PAT model), the uncertain impacts of climate change on agriculture, and ensuring that increasing populations in the world's poorest regions have enough to eat. The authors propose several solutions to increase food production. These include technological innovation, reducing food waste, and changing diets so that people consume less meat and other energy intensive foods. Recall from the very beginning of this chapter that creating a sustainable world requires altering individual behavior and consumption patterns, engaging values and changing social norms, promoting technological advances, and fostering the social, political, and economic institutions necessary to guide individual actions towards sustainable behavior. All of these factors are involved to some degree in the solutions proposed by Godfray and his colleagues.

Cascading Effects. When different components of SES are very strongly interconnected, there is a potential for **cascading effects** that are often rapid and sometimes unpredictable. Cascading effects occur when the effect of a small action on the components or interactions among the components in a system is amplified, such that the small action snowballs into a much larger impact on the system. This is also referred to as the *butterfly effect*. It is important to note that the action can be natural or human-caused. For example, an equally destructive wildfire can be ignited by a natural lightning strike or a cigarette thrown out a car window. Either can be viewed as the "match that starts the fire" in a small square inch of ponderosa pine forest,

cascading effects a chain of events set off by an action in one part of a system that results in relatively larger and typically unpredictable impacts on the rest of the system.

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BOX 2.3 CONCEPT ILLUSTRATION

The 2007–2008 Food Crisis is a good example for illustrating just how interconnected the world is today. At the end of 2007, almost 40 countries around the world were in a food crisis. Food became extremely expensive at this time. The countries in Africa were the worst hit, such as in Somalia where grain costs rose 350% and in Ethiopia by 500%. As you may remember from watching the news during this time, there was civil unrest as people protested high food prices in cities around to world. The cause of the food crisis is still up for debate, and most agree that there was no single cause, but multiple causes (**Figure 2.5**), which is an idea discussed on more detail in Chapter 3 in Section 3.2 in causal chain analysis. The major proposed causes of the food crisis are increased use of *biofuels*, *rising oil prices*, *climate change*, *more demand for meat*, and *market speculation*.

When *biofuels* are made from food crops such as corn, there is less food available to eat. With a lower supply of food and an unchanged demand, the price of food rises. *Rising oil prices*

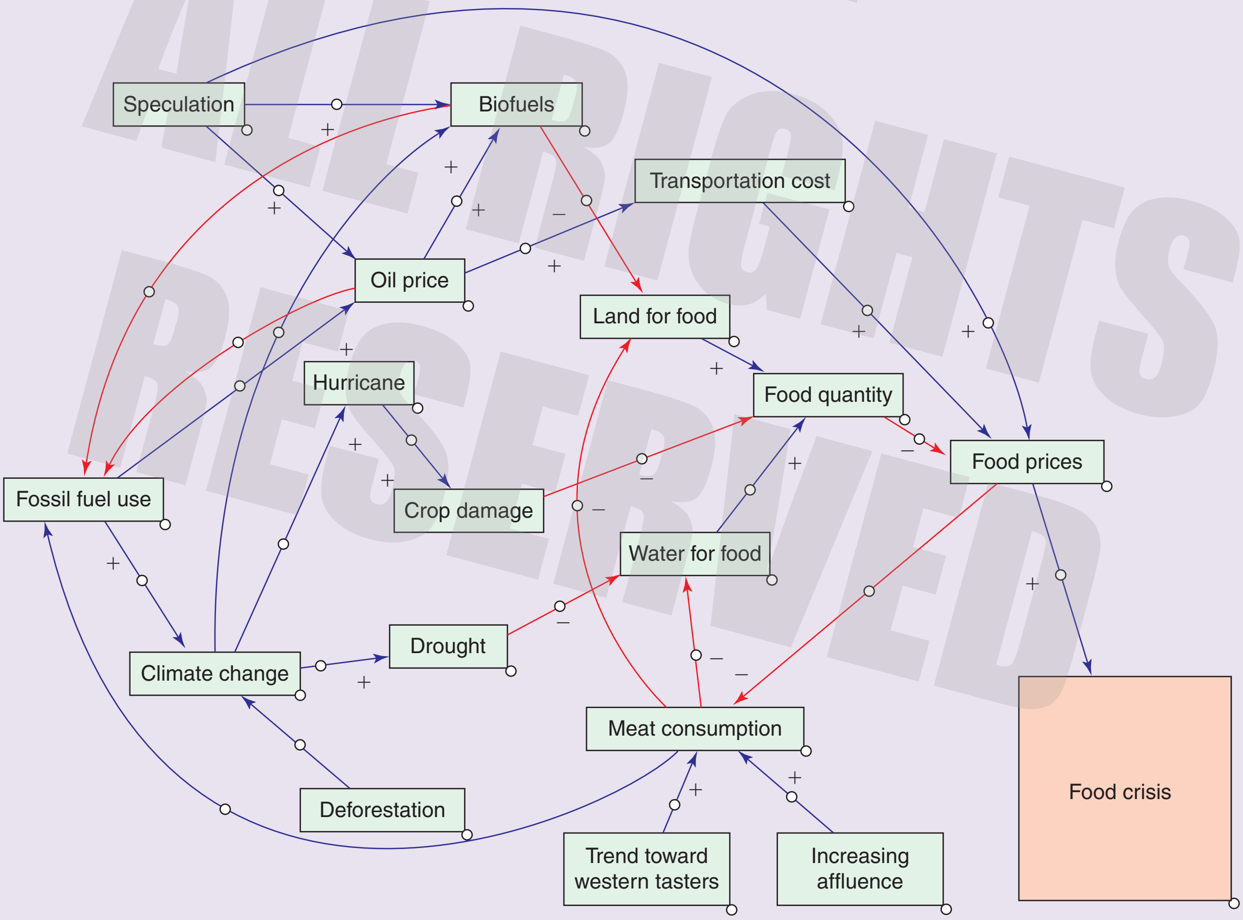

Figure 2.5

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contribute to the food crisis directly and indirectly. The use of oil-based synthetic fertilizers and gasoline for transportation to market directly affects foods prices when oil prices rise by raising food production costs. Indirectly, high oil prices provide an incentive to seek out other fuel sources and contribute to the growth of biofuels. Severe droughts and flooding due to *climate change* can decrease food supplies, leading to an increase in food prices by reducing harvest levels. Some countries were impacted by this more severely than others. For example, wheat harvests in Australia were 50 to 60% below normal levels and 15% below in the United States. Overall, global grain production fell by 1.3% just before the food crisis. Rising populations and increased wealth in developing countries, such as India and China, led to *more demand for meat*. It takes about 7 kg of grain to produce 1 kg of beef. Like with biofuels, diverting grain from the food supply to another use decreased the amount of grain available for humans to eat. Again, reduced supply caused food prices to increase. The role of *market speculation* is the least certain, but many suspect that this played a role as well. Basically, market speculation involves betting on the future price of some commodity. In this case, the speculators bets were wrong, and this resulted in increased food prices. This example illustrates the vast interconnectedness of our world today and how problems in a few regions of the world can threaten the entire global system. The choice to use more biofuels in the United States can lead to people starving in Ethiopia.

which eventually cascades up to one pine tree then to another tree and then the entire forest ecosystem and finally on to an entire landscape of forest, desert, scrub oak, and grassland ecosystems. This idea can also be applied to human systems. For example, the invention of Facebook occurred on a single college campus (Harvard) almost a decade ago and was initially used by only Harvard students. It was eventually expanded to other colleges in Boston and then to all Ivy League schools in the United States. It was later opened to high school students, then to anyone over age 13. Today, it is used by almost 1 billion people worldwide. This one innovation by a few college students has cascaded through socio-technical systems to change how people interact and connect with one another socially.

Understanding cascading effects helps understand problems in SESs, but it can also help find effective solution options by identifying **intervention points (aka. leverage points)**. These are locations in a system where a small change in a component or an interaction can lead to a large change in the overall system. If intervention points can be identified, more effective transitions to sustainability might be devised. A few small and effective actions aimed at problem solving taken in one part of the system can cascade through a system to have a large overall impact that can move the system toward sustainability. Like the lightning strike or cigarette that starts the fire, one small action at an intervention point can ignite major changes toward sustainability. Such interventions in SESs can have consequences that reach far beyond the initial effect to create changes in the systems at other places and time periods.

intervention point (aka. leverage point) an efficient place to intervene in a system because a relatively small change or effort ends up causing a large overall shift in the behavior of an entire system.

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scale a reference by which to classify, arrange, and understand internal system components and their interactions in relation to their external environment.

Multi-Scalar SESs. Sustainability challenges exist at multiple **scales**, and all scales must be considered when resolving these problems. This makes defining system boundaries, based on the internal system components and their interactions on the one hand and the external environmental on the other, important but also seemingly arbitrary or fuzzy at times. SES scales can be both spatial (local, national, international) and temporal (now, next year, in a century). Thus, changes that impact SESs can occur on very small to very large spatial scales. For example, both a small pine bark beetle and human-caused global climate change impact forests. The 5 mm long mountain pine bark beetle is about the size of a grain of rice. Beetle populations play an important role in the natural life cycle of forest ecosystems in the western United States and Canada by infecting old, weak trees to make room for new ones. When trees are infected and die, their pine needles turn from green to red. The most severe destruction of forests by this beetle ever observed, from Alaska to southern California, began in the early 1990s and continues to the present day. Increased temperatures and drought in these regions resulting from global climate change are thought to be a major factor. Higher temperatures promote larger beetle populations by speeding up reproduction and decreasing mortality during previously cold, harsh winters. In addition, drought makes trees more vulnerable to beetle attack. Although the forest ecosystem may be the system of analysis around which boundaries are drawn in this case, both changes in components or interactions at small spatial scales within the system (e.g., a tiny beetle) and in the external environment outside of the system at large spatial scales (e.g., global climate change) both influence the system.

In addition to spatial scale, temporal scale is also a factor. Impacts on SESs occur on time scales ranging from seconds to millennia. For example, both asteroids and volcanoes have impacted global biodiversity in the past. The Cretaceous-Tertiary mass extinction wiped out 70% of all biodiversity on earth. One proposed cause of this extinction is an asteroid impact that took seconds. However, it is the cascading effects of this impact that are thought to have caused the actual extinction. The impact blasted dust and aerosols into the atmosphere, which blocked sunlight from reaching the earth. Plants could not photosynthesize without sunlight and died. Because plants are the base of food chains, the impacts of their death cascaded through food chains to impact all other organisms higher in the food chain. The other proposed cause of this extinction was the 800,000-year-long volcanic eruption known as the Deccan traps. This eruption could have contributed to mass extinction in a similar way that the meteor did by adding dust and aerosols to the atmosphere. It may have also caused climate change by adding massive amounts of CO_2 to the atmosphere. When analyzing sustainability problems, spatial scales ranging from the tiny bark beetle to the entire global atmosphere and time scales ranging from milliseconds to millions of years must be considered. Solutions must also be implemented at multiple scales to ensure sustainability at various locations around the world today and into the future to ensure intergenerational equity.

Complexity Level 2: Complex Systems. Complex systems exhibit certain **dynamics**, or patterns of change over time, that distinguish them from the simple systems described in the first part of this section. One major distinguishing feature of complex systems is that system components can change over time as a result of the interactions among them. Cars and bicycles, on the other hand, are not complex systems because their components (e.g., gears, crankshaft, wheels) do not change as a result of interaction with other components through physical forces. In complex systems, the size of system components can change over time as a result of interactions, such as when trees grow in a forest due to photosynthesis or the number of producers in an economy grows due to increased purchasing by consumers. In systems-modeling jargon, components are referred to as **stocks (aka. reservoirs)** to reflect the amount of energy, materials, and information that they contain. System interactions are referred to as **flows** to represent the amount of energy, materials, and information added to or removed from components over a certain period of time.

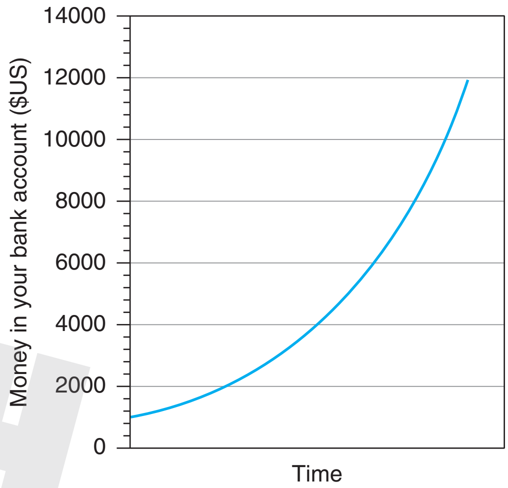

Figure 2.6

Complex systems also exhibit **feedbacks** that can lead to **nonlinear** behavior. Feedbacks occur in complex systems when the component themselves regulate the processes defining the interactions among components. For example, two components of your personal finance systems are the banking institution where you do your business and your own personal bank account. One interaction between the banking institution and your bank account is the addition of money to your account based on a savings account interest rate as defined by your banking institution. The amount of money being added to your account is regulated by the amount of money in your account at any given time. For example, if the interest rate is 1% and you have $1000 in your bank account to start, then $10 is added when interest is compounded. The next time interest is compounded, the amount added is $10.10 because it is based on the new amount of money in your account which is $1010. If you carry out these calculations farther into the future, you will see that your bank account grows in a nonlinear fashion as shown in **Figure 2.6**. This type of regulation of interactions among system components by the size of a component at any given time leads to nonlinear system behavior over time. These dynamics are not exhibited by simple systems, which tend to behave in linear ways. For example, if the chain ring (system component) on a bike were made to move faster by more intense pedaling, the physical forces (system interaction) that make it move would not change. This is in contrast to the way that the amount of money deposited in your bank account (system interaction) changes when there is more money existing in the account (system component).

Feedbacks not only cause systems to behave nonlinearly, but they can also result in unpredictable changes that contribute to uncertainty about how

dynamics patterns of change exhibited by a system over time.

stock (aka. reservoir) a system component that reflects some quantity of energy, material, or information contained in a system.

flow a system interaction that represents the rate at which some quantity of energy, material, or information is transferred among system components or between the system and its external environment.

feedback a specific type of interaction among system components, or with the external environment, such that the outcome of some process returns to affect the factor that originally initiated the process.

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nonlinear an interaction defined by the fact that the magnitude of the factor causing some interaction in a system and the actual outcome of that interaction are not proportional.

shifting dominance a constant interplay between the two general types of feedback in a system that compete with each other for dominance that determines the system's overall behavior at any given time.

threshold (aka. tipping point) the point beyond which a system shifts nonlinearly to a different regime

regime (aka. alternative stable state) the dynamic and constantly changing yet characteristic pattern of conditions under which a system can exist and by which it supports certain functions or purposes

regime shift a typically nonlinear change process by which a system transitions from an existing regime to a new regime under which the system supports different functions or purposes than before.

systems will behavior over time. Because of a **shifting dominance** between two major types of feedbacks, complex systems sometimes cross **thresholds (aka. tipping points)** into new **regimes (aka. alternative stable states)**. These **regime shifts** result in a completely new systems often characterized by a different set of interconnected components structured in new ways, such that the interactions among the components and feedbacks now support some new purpose. In short, regime shifts result in fundamental changes in system properties and behavior that may or may not be sustainable. In addition to regime shifts, feedbacks operating *within* a given regime led to system **fluctuations** that vary the **state** of the system *within* that regime. Distinguishing normal systems fluctuations from complete regime shifts, and what system behavior looks like as it approaches a regime shift, is an important part of understanding SES complexity.

All of the bolded concepts in the previous paragraph will be thoroughly defined and discussed in much more detail in Chapter 5. For now, a few of these concepts are expounded on briefly as a general introduction to the factors contributing to uncertainty in complex systems. A simple way to understand how regime shifts are characterized by nonlinear and unpredictable system behavior is with a rubber band analogy. If you stretch a rubber band and then let it go, it will rebound to its original size. However, if you stretch it too far, it will break. Pick up a rubber band and begin to stretch the rubber band slowly using a constant pulling force. This is linear behavior because, for each additional unit of force that you apply, the rubber band stretches the same additional distance. The nonlinear behavior starts as the rubber band approaches its breaking point. At this point, the rubber band feels more rigid and you have to apply much more force to move the rubber band the same distance until it finally snaps apart. When the rubber band breaks, you see a sudden change and exact timing of that change was unpredictable. When the rubber band snapped, the rubber band system crossed a threshold into a new regime that fundamentally serves a different purpose. The rubber band used to serve a purpose of holding a stack of cards together (Regime 1), but now it is a broken rubber band (Regime 2). It can still be used as a weapon to fend off your annoying little brother, but it can no longer be used to hold together a stack of cards in the same way.

Sudden shifts in complex systems from one regime to another occur in both natural and human systems. Scientific analysis of these systems can often alert us to heightened risks of such sudden change, but it cannot yet forecast the exact point when change will occur. The importance of understanding these tools for thinking about complex systems behavior when it comes to sustainability of SESs is illustrated with an example of a regime shifts in a coral reef ecosystem in **Box 2.4**. Coral reefs support high biodiversity, which contributes to ecosystem health, human well-being, and economic vitality.

It is the shifting dominance between two different types of feedbacks that result in complex systems shifting from one regime to another. **stabilizing feedbacks (aka. negative feedbacks)**, tend to keep a system in its current regime. They occur when two components of a system cause each

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BOX 2.4 CONCEPT ILLUSTRATION

Much of the time, change in ecosystems is linear. It is gradual and predictable. However, there are many examples of rapid nonlinear changes in ecosystems that surprise us. Coral reefs (**Figure 2.7**) have experienced rapid shifts in species composition from mostly corals to being dominated by algae. Two interacting factors often push a coral reef system toward this sudden change: overfishing and high nutrient inputs. In coral reefs, herbivorous fish graze on reef algae in the same way that cows graze on grass. Overfishing of herbivorous fish in reefs results in massive algae growth, just as grass would grow abundantly if cows stopped eating it. Algae also need nutrients to grow and more nutrients result in faster growth. Nutrient inputs to coral reefs include sewage inputs and runoff from agricultural fields. Overfishing and excessive nutrient inputs to reefs can occur over many decades to centuries with no major change. Then suddenly, in a matter of weeks or months, the species composition can rapidly shift from coral-dominated to algae-dominated just as a rubber band suddenly breaks. Also like the rubber band breaking, these changes in coral reef systems can be irreversible and unpredictable. The two different reefs have different properties. Algae-dominated reefs harbor much less biodiversity than coral-dominated reefs; this can impact many human activities ranging from commercial fishing to tourism to subsistence reef harvesting.

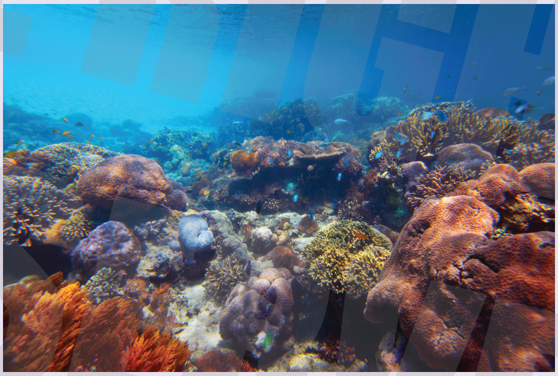

Figure 2.7 Coral-dominated reef

other to change in opposite directions. For example, an air conditioner keeps a house cool. If the thermostat is programmed to keep the house at 75ºF and the internal temperature of the house is currently 8ºF, the thermostat will turn on the air conditioner. Once the temperature in the house reaches 75ºF, the thermostat will signal the air conditioner to turn off. The two components of this system are temperature and the air conditioner. They cause each other to change in opposite directions: When the temperature goes above 75ºF, the air conditioner causes the temperature to drop by turning on. When the temperature drops below 75ºF, the air conditioner causes the temperature to rise by turning off. As long as this stabilizing feedback continues to operate, the internal temperature of the house will remain the same and will not be significantly impacted by outside changes in temperature.

fluctuations periodic changes in the state of a system within a given regime that do not constitute a regime shift.

state the conditions under which a system exists at any given time.

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stabilizing feedback (aka. negative feedback) a general feedback type that keeps a system in its current regime.

reinforcing feedback (aka. positive feedback or amplifying feedback) a general feedback type that causes a system to change and ultimately shift to a new regime.

albedo the fraction of solar radiation that is reflected from a surface rather than absorbed.

Feedbacks do not always create stability in complex systems and can instead result in change. An **reinforcing feedback (aka. positive feedback or amplifying feedback)** causes a system to change. Amplifying feedbacks cause systems to shift from one regime to another, such as in the examples of the rubber band and the coral reef. They occur when two components of a system cause each other to change in the same direction. Using another climate change example, there are strong amplifying feedbacks operating when it comes to the melting of Arctic sea ice. Since the 1970s when sea ice monitoring began, sea ice extent has dropped from an average of 7 million km^2 to 5 million km^2 in recent decades. This rapid melting is largely the result of an amplifying feedback between sea ice extent and temperature. **Albedo** is a measure of the amount of solar radiation reflected from a surface rather than absorbed. When solar radiation is reflected due to a high albedo surface, it does not warm the surface. When it is absorbed due to a low albedo surface, it does. Higher temperatures in the Artic have resulted in melting sea ice. Ice has a high albedo, so it reflects a lot of sunlight (about 30–40% reflected). As more and more ice melts, more water is exposed. Water has low albedo (reflects < 10% of sunlight), so it absorbs more sunlight and heats up more than ice. This increases temperature in the water surrounding the ice, which causes the ice to melt even faster. The amplifying feedback operates between two components of this system: ice extent and temperature. Ice extent declines, temperatures increases. This causes ice to decline even more and temperature to increase even more. Eventually, when this amplifying feedback dominates over the stabilizing feedbacks keeping the system in its current regime (Regime 1: Ice-Covered Arctic), the Artic system will shift from to a new regime (Regime 2: No Ice Cover). Like the broken rubber band and the algae-dominated coral reef, an iceless Artic will no longer support the same purposes as an ice-covered Artic. For example, polar bears rely on ice as a platform for hunting seals, which are their main food source. An iceless Arctic will not be a system capable of supporting polar bears in the same way.

inertia the momentum of a system that keeps it moving in a certain direction and is it difficult to resist when attempting to stop the system or steer it in a different direction.

In addition to playing a part in regime shifts, feedbacks also contribute to system **inertia**. This is another property of complex systems contributing to uncertainty about their behavior. You may remember from a physics class that inertia has to do with an object's momentum, which keeps it moving in a certain direction. An object with a large momentum requires a lot of force to stop or steer in a different direction. Inertia in kind of like this, but has to do with feedbacks. A system with strong inertia has a tendency to respond to external impacts with reinforcing feedbacks that send it strongly off into some direction. Once the system is moving off in that direction, it is difficult to stop it or steer it in another direction. Inertia results in a slow or delayed response of a system to some additional impact that will eventually cause it to stop or steer it in a certain direction.

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Human societies regularly demonstrate inertia when confronted with the need for change. Individuals tend to align their own beliefs and attitudes with those people who make up the social group to which they are strongly tied, such as their family, friends, profession, or community. This tendency is so strong that even if individuals are presented with evidence that does not support their current beliefs, they will usually maintain them. This can make it incredibly difficulty for human societies to adapt to changing conditions, which can threaten their future survival. In his 2009 book *Collapse: How Societies Choose to Fail or Succeed*, scientist Jared Diamond argues that a society's response to a problem threatening its survival is one of the most important factors determining whether the society collapses or succeeds. One example is the Icelandic Vikings, who moved from Europe to colonize Greenland in the 10th century. In their homeland, they relied on cows as a major food source and brought them to Greenland. Even though cows were not as well adapted to the harsher, colder Greenland climate, they continued to depend on them for food and failed to adapt to their new environment by learning techniques for efficiently hunting local food sources such as seal and caribou. In the early 15th century, Greenland plunged into an ice age, which created conditions under which the cattle could not survive. The Greenland Viking society experienced famine and eventually disappeared.

Inertia is also a property of natural systems. It can lead to continued change in a system even after the factor driving the change has stopped directly impacting the system. The climate system contains a lot of inertia. This is one reason the exact timing and extent of human-caused climate change is difficult to predict. For example, CO_2 emissions to the atmosphere are a major factor driving climate change. Even if humans stopped emitting CO_2 today, sea level rise due to thermal expansion of ocean water would continue for hundreds of years. Thermal expansion is the change in volume that a body of water experiences in response to a change in temperature. In the mid- to late-20th century, sea level was rising at a rate of about 2 mm/year. However, the rate of thermal expansion has increased to *more than* 2 mm/year at present. This rate would continue to rise even if CO_2 emissions were stopped this instant. To understand why, just think of what happens when you heat water on your stove. When you place a pot of water on a burner, it does not boil instantly. It takes time. The oceans behave in the same way, but the response takes longer (centuries rather than minutes for water boiling on a stove) because the global ocean is so immense. The melting of continental ice sheets due to climate change will continue for thousands of years, even if we stop CO_2 emissions today. Ice melting also does not occur instantaneously when exposed to heat. Put an ice cube out in the sun and you will see that it takes a few minutes to melt. Because the length of time between an actual impact on a system and the expression of the full consequence of that impact is difficult to predict, system inertia adds an element of uncertainty.

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complex adaptive system (CAS) a system capable of evolving over time in a manner that helps it adjust to changing conditions and typically in ways that promote its survival.

Complexity Level 3: Complex Adaptive Systems. In addition to the features of simple systems and complex systems already mentioned, **complex adaptive systems (CAS)** have several features that allow them to adapt to changing conditions often in a way that promotes their survival. Thus, the distinguishing features of CASs are that adaptation to changing conditions plays a large role in their dynamic behavior and in defining their complexity. As laid out by Melanie Mitchell in her book *Complexity: A Guided Tour,* CASs have three major characteristics that defining their complexity. First, they exhibit emergent properties that cannot be explained by the behavior of each individual system component alone. In other words, the whole is greater than the sum of its parts. This behavior emerges somewhat spontaneously, without a central controller organizing and directing individual component behavior, such that CASs seem to "take on a life of their own." Second, CAS behavior is determined by a two-way exchange of matter, energy, and information among internal system components and process on the one hand and the environment external to the system on the other. This shapes the behavior of CASs over time. Finally, CASs adapt their behavior to changing conditions over time by passing on and receiving information through learning and evolution. Following a brief introduction to adaptive cycles at the end of Chapter 5, which is a feature of CASs, other tools for thinking about CAS complexity are covered in great detail in Chapter 6.

All of the tools for thinking about SES complexity introduced here will be applied or expanded on in later chapters of this textbook. The tools are useful for understanding the SESs in which wicked problems are embedded. An overview of a problem-solving framework, called Transformational Sustainability Research (TSR), that can actually be used to go about resolving wicked problems based on an understanding of their complexity is introduced in the final section of this chapter.

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Section 2.2: Resolving Sustainability Problems

Core Question: How can wicked sustainability problems be resolved?

Three general topics will be presented in this section. First, a general problem-solving framework for wicked problems will be introduced. The framework is used by sustainability scientists and professionals to solve wicked problems. Only a brief overview of the problem-solving framework will be given here, but each component will be discussed in more detail in the chapters that compose the remainder of this textbook. Second, the importance of considering tradeoffs among environment, society, and economy when resolving wicked problems will be presented within the framework of weak versus strong sustainability. Finally, the importance of transdisciplinarity and participatory approaches throughout the entire problem-solving process will be discussed.

Section 2.2.1—Overview of the Transformational Sustainability Research Framework

Key Concept 2.2.1—Current state analysis, future scenarios, visioning, and transition strategies are emerging tools that can be used to resolve wicked sustainability problems.

Professor Arnim Wiek, who is a sustainability scientist at Arizona State University's School of Sustainability, developed a problem-solving framework for resolving sustainability problems. It was developed in his Sustainability Transition and Intervention Research lab at ASU and in collaboration with many international colleagues. The framework, called **Transformational Sustainability Research (TSR)**, builds on various research, planning, governance, and decision-making frameworks, including ideas presented in *Great Transition: The Promise and Lure of the Times Ahead* by the Global Scenario Group. This work was published in 2002 to assess the necessary conditions for a societal transition to sustainability. *Great Transition* asks four key questions: (1) Where are we? (2) Where are we headed? (3) Where do we want to go? (4) How do we get there? It should be noted before moving on that the reference to "we" in these questions is left purposefully broad and vague so that this framework can be adapted to specific contexts around the world for resolving wicked problems. Depending on the specific wicked problem of interest and the stakeholders involved, "we" could mean the members of a small village, residents of a city, all people in a nation, or our global society and humanity as a whole.

Transformational Sustainability Research (TSR) a general problem-solving framework that can be used to understand and resolve sustainability problems.

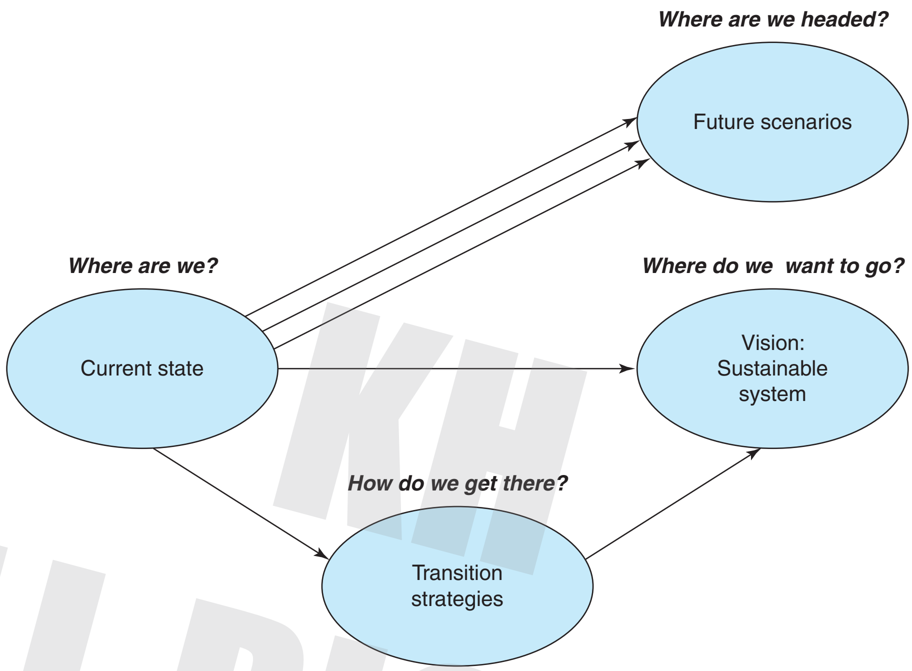

Figure 2.8 **TSR Framework**

> **Current state analysis** a process used to evaluate and understand the present-day situation of a given socio-ecological system, and for a certain wicked problem facing that system, with the aim of producing information and insight for thinking about the future of that system and devising strategies for the transition of that system to a more sustainable future.

The four questions correspond to the four major components of the TSR framework presented in **Figure 2.8**. The first question is answered by analyzing the current state. **Current state analysis** (Chapter 3) involves assessing and understanding the current situation so that this information can be used to think about the future and transitions to a more sustainable future. It involves classifying system drivers, identifying causal linkages among drivers, and a stakeholder analysis to examine the factors guiding human behaviors toward actions that contribute to the current unsustainable situation. This also means considering a number of factors that shape behavior such as rules, regulations, resources, technologies, and the norms, beliefs, and values of stakeholders. The effects of actions for stakeholders in all three pillars of sustainability—environment, society, and economy—should be considered in this analysis as well at the short-term and long-term consequences. After completing current state analysis, a detailed answer can be given to the question: Where are we?

> **indicator** quantitative or qualitative data used to determine the current state of a system, how far it is from some ultimate goal, and which way it is changing or whether it is even changing at all.

During the current state analysis, and also for looking toward the future (Chapter 7) and managing transitions (Chapter 8) to sustainability, **indicators** (Chapter 4) are used to track progress towards or away from sustainability. They are also used to understand SES complexity by distinguishing system fluctuation from more fundamental system change and identifying the *feedbacks* that are stabilize systems or cause them to cross thresholds to become new systems (Chapter 5). Finally, they can be used to understand and track SESs over time that exhibits the levels of complexity characteristic of complex adaptive systems (Chapter 6).

To answer *where we are headed?* and understand the impacts of our present actions on the future, *future scenarios* (Chapter 7) are developed. Sustainability is about long-term perspectives. As a result, the impacts of our actions (or inaction) today on the future must be considered. **Scenarios** are carefully constructed stories about alternative paths a system might take as the current state moves into its future state. It is important to intentionally explore alternative, possible futures because in SES many factors may combine in unpredictable ways that lead to a surprising future. Future scenario development is about trying to anticipate these alternative, plausible futures. Scenarios are developed to identify the events, actors, and processes that might lead to each alternative future. Future scenarios can be based on quantitative models, qualitative narratives, or both. Engaging relevant stakeholders in the scenario development process is critical to promoting social learning, collective understanding, and action.

scenario a carefully constructed quantitative model or qualitative story about one of many plausible alternative pathways a system might take into the future and what its future state might look like.

Future scenarios help figure out where we are headed, but *where do we want to go?* is our **vision** (Chapter 7). The **visioning** process brings together relevant and diverse stakeholders to attempt to reach consensus on where we want our SES to go. Some future scenarios, such as rapid sea level rise followed by millions of climate refuges moving to other countries and destabilizing political systems, are undesirable for a sustainable future. Others scenarios, such as well-planned climate change adaptation measures implemented in today's policies to ensure human well-being in the future if sea levels were to rise, are more desirable. Visioning is used to collectively create a vision for a preferred future state and to set goals for that preferred state. Recognizing that real lasting change takes time, visions are focused on where we want to be in the long-term, typically 20 to 30 years into the future. Visions are developed through a series of meetings that take into account the perspectives and interests of all stakeholders.

vision a desirable future ideal envisioned by a society or a sub-set of society.

visioning the process by which a vision is collectively created by a society or a sub-set of society.

The last part of the problem-solving framework is *transition strategies* (Chapter 8). During this phase, strategies are developed to move from the unsustainable current state to the desired sustainable future vision. One major aspect to developing transition strategies is determining intervention points at a variety of spatial and temporal scales in the system of interest. Intervention points are places or times in an interconnected SES in which a wicked problem is embedded, where the root of our difficulties really reside. If intervention points and required actions for sustainable change can be identified, then leverage can be gained and the capacity to influence the future state of a system through small actions that have relatively large impacts gained. As a result, intervention points are also called *leverage points*. Transitions strategies help us figure out how to steer or guide systems toward sustainability and also how to avoid undesirable future scenarios identified during the scenario development phase. A big part of designing transition strategies is weighing the tradeoffs among environmental, social, and economic priorities that will be necessary for a viable transition to sustainability.

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Section 2.2.2—Making Tradeoffs for Sustainability

Key Concept 2.2.2—Weak and strong sustainability represent two different beliefs regarding the extent to which tradeoffs among environment, society, and economy may be made when resolving sustainability problems.

tradeoff a situation in which one or more aspects of a pillar of sustainability are lost in exchange for gaining one or more aspects of the other sustainability pillars.

weak sustainability a belief that the resources and services provided by natural systems can be substituted by technologies developed by human systems such that extensive tradeoffs can be made among components of the three pillars of sustainability.

strong sustainability a belief that the substitutability of natural system components by technologies developed within human systems is limited such that tradeoffs among the three pillars of sustainability is also limited.

Tradeoffs help us reconcile the inherent conflicts among the environment, society, and economy pillars of sustainability. These conflicts are inherent because, as the integrity of one or more pillars is eroded, all other pillars are inevitably added to or enhanced. For example, economic development unavoidably involves some degree of natural resource extraction and pollution. This adds to the economic pillar, in terms of GDP growth, but takes away from the environment pillar. Economic development to alleviate poverty by meeting people's basic needs requires use of natural resources and creates pollution that compromises the integrity of the environment. This adds to the society pillar, but again takes away from the environment pillar. Under our current economic system, economic development also takes away from society in some instances. This is evidenced by the rise of labor unions and child labor laws to address these problems, and the cases of sweatshop labor and worker exploitation that still occur around the world today. Solving almost all problems related to sustainability involves making tradeoffs. There are rarely perfect solutions with no costs to the environment, society, or economy, and there are often winners and losers. Striving for win-win-win situations in which some action enhances sustainability by simultaneously adding to all three pillars is the ideal goal. In reality, this is difficult to achieve.

There is disagreement between advocates of **weak sustainability** and **strong sustainability** regarding the extent of tradeoff that is possible or desirable. Advocates of weak sustainability view the resources and services provided by natural systems as interchangeable with technologies developed by human systems. They are not concerned about environmental degradation because they believe technology alone can solve sustainability problems. In other words, nature has substitutes. In this view, it is possible to make tradeoffs between the environment and economy pillars without end. In the words of economist Robert Solow in 1974: "If it is very easy to substitute other factors for natural resources, then there is in principle no "problem." The world can, in effect, get along without natural resources, so exhaustion [of natural resources] is just an event, not a catastrophe." For example, the cellulose used to make paper pulp comes from trees. If all trees were cut down to make paper pulp and none remained, the cellulose from other natural resources such as hemp or agricultural wastes from corn stalks could act as substitutes with the proper technologies. The weak sustainability view is understandable because technology has solved many human problems in the past, such as sanitation with sewage treatment and disease with medical advances. It is reasonable to think that it will in the future.

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Advocates of strong sustainability would disagree. They warn that we must be careful of the extent to which we make tradeoffs because there are limits to how much we can substitute the elements of one pillar for those of another. If we go beyond this limit, they argue, irreversible damage will occur as systems shift from one regime to another. Because human and natural systems are so interconnected, tradeoffs that are too large will leave one or more pillars too degraded, and this will harm the entire socio-ecological system. For example, as mentioned above, economic development takes away from the environment and adds to the economy. However, if too large of a tradeoff occurs and too much is taken away from the environment, it will become so degraded that economic development will no longer be possible and the resources required for alleviating poverty will disappear. Although some tradeoffs are usually inevitable, there is a limit. Strong sustainability arose from the fact that humans have traditionally given the economy, in terms of GDP growth, priority over the environment and society. Advocates of strong sustainability would also argue that technology cannot replace many resources and ecosystem services. For example, one could argue that a water treatment plant could replace the water purification services offered by ecosystems such as forests and wetlands. However, how can we replace clean air with technology? What about photosynthetic processes that form base of our food chains or the global water cycle? Advocates of strong sustainability would argue that we cannot and that sustainability requires behavioral change, such as reduced consumption patterns, not only green technology development.

Section 2.2.3—Participatory and Transdisciplinary Approaches

Key Concept 2.2.3—Including a diversity of stakeholders is key to resolving sustainability problems, as it ensures that both local and expert knowledge are incorporated into problem-solving processes and that solutions have "staying power."

Sustainability means different things to different people. The weak sustainability versus strong sustainability debate is one of many examples of conflicting perspectives regarding what needs to be done to move our societies toward sustainability. It is important to incorporate these different perspectives into every stage of the problem-solving framework by engaging all relevant stakeholders in the process. Traditionally, we have relied on mostly expert knowledge for problem solving. However, this knowledge alone has failed to solve wicked problems and we need a new approach. This new approach is generally referred to as a **participatory approach**. At its most basic level, this simply means that local communities are included in the problem-solving process rather than only involving scientists and

participatory approach a democratic problem-solving process that incorporates both the specialized knowledge of experts and the practical knowledge of local communities as a basis for defining and understanding problems and devising solution options.

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co-production a process through which knowledge about a situation is generated by blending the specialized knowledge of experts with the practical knowledge of local communities.

transdisciplinary knowledge and understanding based on both the specialized expertise of academic experts and the practical real-world know-how of communities outside of a university.

government officials. When communities work together to resolve problems, the approach is often referred to as *bottom-up*. A *top-down* approach is when primarily natural scientists, social scientists, government officials, academics, and other experts work on finding solutions. What is needed is a merger of the bottom-up approach with the traditional top-down method, which has failed to successfully resolve sustainability problems on its own. There are several advantages to a bottom-up approach. Local knowledge about the current state of situation may be more accurate than that of experts that come into the community as outside observers of a problem. As conditions change through time, local communities will observe this and management strategies can be adapted to changing conditions. When a solution is developed, communities may be the best judge of whether the proposed solution will be viable in a real-world local setting.

Another advantage of community participation is that it can provide communities with the capacity, in terms of education and skills, to continue a project after the volunteers leave or after the money stops flowing. For example, in one instance U.S. Peace Corps volunteers were working to help people in a remote village to build a well for easy access to water. About midway through the project, a wealthy company swooped in to build wells immediately and at no cost to the villages. At first, the well was fine. However, a year later after the Peace Corps volunteers and the company had left, the wells broke. The villagers did not know how to fix them and they were back to square one. The ability of communities to address future problems is sometimes more significant than seeing immediate results. Finally, community buy-in or acceptance of a project is extremely important to the longevity and staying power of a plan for action toward sustainability. If the solution that you implement is not the solution that people want, then you are wasting time and resources. Community-engagement in problem solving can be a costly process, in terms of time, effort, and money, but it is more likely to lead to a long-term, sustainable solution than a "quick-fix" expert solution.

Figure 2.9

Many types of knowledge, both expert and local, are needed to resolved wicked problems. When a singular perspective on a problem is taken, like in the *Blind Men and the Elephant* parable, the complexity of the problem cannot be seen. When experts work together with local communities on sustainability problems, it is often referred to as the **co-production** of knowledge. This can be viewed as expert knowledge embedded into a specific local situation that has its own practical knowledge (**Figure 2.9**). The new knowledge that is produced from this process is referred to as **transdisciplinary** knowledge. The importance of interdisciplinary problem solving has been recognized for some time now. This is when experts from many disciplines, such as biology, political science, and sociology, attempt to integrate concepts and ways of thinking from their individual disciplines to solve a problem in ways that would not have be possible using only a single discipline. However, all of this knowledge is still *expert knowledge.* Transdicisplinary knowledge goes beyond this by moving into the real world to include *practical knowledge* and ways of thinking in addition to expert knowledge. This book is focused on solving sustainability problems in the real world using the TSR framework just introduced. Case studies will be presented throughout these chapters to give you examples of how practical knowledge can contribute to problem resolution. However, each local problem is different, so all possible ways to incorporate local knowledge into problems is different. If you want to get real experience with this right away, then go out there and start resolving wicked problems, and find out for yourself!

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End of Chapter Questions

General Questions

1. Fill in the table that follows to briefly and generally explain why each of the sustainability issues listed in the first column is a wicked problem. The six characteristics of a wicked problem discussed in this chapter are

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listed across the top of the table. Explain how each problem exhibits each of the six characteristics.

	Vague Problem Definition	**Undefined Solution**	**No Endpoint**	**Irreversible**	**Unique**	**Urgent**
Climate Change						
Biodiversity Loss						
Population Growth						
Deforestation						
Overfishing of the Oceans						
Nonrenewable Resource Use						
Poverty						
Economic Growth and Overconsumption						
Human Population Growth						

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2. In order to resolve wicked problems, tradeoffs must be made among the three pillars of sustainability: environment, society, and economy. The extent to which these tradeoffs can be made is expressed by the two different belief systems of weak sustainability and strong sustainability. Determine whether each of the following statements expresses the weak sustainability or the strong sustainability viewpoint.
   - **a.** Running out of nonrenewable, energy-dense fossil fuel energy resources is not a problem. When these resources do run out, new equivalent resources for energy production will be discovered and human society will be able to continue at its current levels of consumption and economic growth.
   - **b.** Indigenous societies of the Amazon basin have subsisted in the rainforests of this region for centuries. During this time, much of their well-being was derived from these traditional subsistence activities. While some commercial logging of tropical hardwoods in this region is okay, too much will be very harmful to the well-being of these indigenous societies.
   - **c.** Bees and other insects provide a valuable ecosystem service because they act as pollinators for crops that provide human societies with food. Without them, crops would not be pollinated and would not produce food. If bees and other pollinators become extinct, there is no technology presently available or that could be invented to replace this ecosystem service. Therefore, bees and other pollinators are essential for the survival human societies and should be protected from extinction.
   - **d.** Indigenous societies of the Amazon basin have subsisted in the rainforests of this region for centuries. During this time, much of their well-being was derived from these traditional subsistence activities. Today, commercial logging of tropical hardwoods occurs in this region. This activity is beneficial to the well-being of indigenous societies because it leads to economic development. Any well-being experienced by indigenous societies in past centuries through traditional subsistence activities will be replaced by the well-being brought by economic development.

Project Questions

This is the first of many Project Question sections located at the end of each chapter. Beginning with this chapter, you will choose a wicked problem to focus on throughout this book. This might be a case study that you will work on virtually in the classroom or a problem that you will try to actually resolve in the real world. The problem you choose might be focused on many different issues, including food, water, energy, waste, transportation, human health, poverty, population growth, and many others. You will need

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to conduct research and gather additional information about your specific problem in order to fully answer the questions in the Project Question sections throughout this book, and your answers will require continual revisions as you incorporate new information. The Project Question section for this chapter is focused on beginning a current state analysis, which is the first step in the sustainability science problem solving framework presented in this textbook (Figure 2.5).

1. **Define Your Wicked Problem:** Define your wicked sustainability problem using the six characteristics of a wicked problem, as you did for several wicked problems in Question 1 in the General Questions section. Your focus could be on one of many possible scales, such as a problem relevant to a small town, large city, county, state, country, region, or even our entire global society. You may want to skip back-and-forth between this question and the next, as it may help to answer both questions simultaneously.
2. **Define Your System:** As mentioned in the previous question, your wicked problem could be focused on a town, city, county, state, country, region, or our entire global society. Being specific about the scale of your problem helps you define your system. Define your system by detailing the system components and the interactions among those components, such as by using the boxes to represent components and the arrows to represent interactions as shown in Figure 2.4. Also define the boundaries of the system, such that the system components and interactions among those components lie within the boundaries and the other aspects important to the wicked problem lie outside of the system boundaries. Remember, wicked problems are embedded in open systems, which means that the components inside of the system boundaries interact with those outside of the boundaries. Also, recall that the purpose of defining your system is to help you simplify the complexity of the real world and that no one system definition is absolutely correct. The system that you define here is a first draft and will likely be revised many times as you work through the Project Questions sections at the end of each chapter of this book and as you gather more information about the wicked problem that you have chosen to work on.

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