Chapter 2 from: Henrik Selin and Noelle Eckley Selin, 2020. *Mercury Stories: Understanding Sustainability through a Volatile Element*. Cambridge, MA: MIT Press. Posted with permission.
To purchase the book: https://mitpress.mit.edu/books/mercury-stories

2 Analyzing Human-Technical-Environmental Systems

Systems-oriented approaches are common in many fields of study, and they are also appropriate for studying sustainability issues. Analytical frameworks provide tools to help identify components of individual systems, examine how these components interact, and explore how these interactions can be changed over time, including toward greater sustainability. We believe that a new analytical framework can help readers with different backgrounds better examine and understand complex sustainability issues from an interdisciplinary systems perspective. In this book, we develop such a framework, applying the perspective of a human-technical-environmental (HTE) system in the context of institutions and knowledge, together with a matrix-based approach. In this chapter, we outline our analytical framework, which we call the HTE framework, and describe how we use it in part II to examine five topical systems involving mercury.

The extraction and mobilization of large amounts of mercury through society and the environment over millennia reflect a broader pattern of how humans have interacted with and depended on the natural world. For much of human history, people's interactions with the environment (and the consequences of those interactions) were largely local, as societies remained small and human mobility was limited. In turn, local environmental conditions shaped much of the early human development that relied on the availability of food, shelter, and energy, and on the ability to ward off predators and pests. Human ingenuity and population growth gradually expanded the scope and depth of these interactions over centuries, in the process fundamentally reshaping relationships between human societies and their surrounding environments. The collective scope of these interactions increased dramatically when the Industrial Revolution began in Europe and North America in the second half of the 1700s, and has further accelerated since the mid-twentieth century (Turner et al. 1990; Steffen et al. 2007).

Advances in knowledge, especially over the past three hundred years, led to the development and application of technologies with far-reaching social, economic, and environmental consequences. These technologies were introduced alongside new institutions that influenced human connections and decisions at an increasingly global scale. Many of these developments in knowledge, technology, and institutions had profoundly positive effects on human prosperity. Most humans live dramatically longer, healthier, and more productive lives than their ancestors did several generations ago. Improvements in production techniques and transportation led to the manufacturing and trade of more and cheaper goods, increasing material standards of living to previously unmatched levels. These benefits are widespread, but they vary sharply, both within and across societies, among people at different levels of income and wealth. In addition, some technologies and institutions had vastly negative environmental consequences, many of which were both unintended and unanticipated.

There is no place on the planet that remains truly unmodified by people. Experts argue that human pressures have replaced natural factors as the main drivers of environmental change, and that the magnitude of these pressures have become so pervasive and profound that they "are pushing the Earth into planetary *terra incognita*" (Steffen et al. 2007, 614). Some analysts suggest that the overwhelming influence of people on the environment represents a new geological epoch, called the Anthropocene (Crutzen and Stoermer 2000). The Anthropocene is viewed as fundamentally distinct from the Holocene ("recent whole"), the postglacial geological epoch of the past 11,700 years (Malhi 2017). The argument that Earth is a human-dominated planet draws attention to the importance of protecting the interacting physical, chemical, and biological cycles and energy fluxes that support life on the planet (Steffen et al. 2007). On a finite, bounded Earth, "everything is connected to everything else" (Sterman 2011, 23). This means that fully understanding social, technological, or environmental factors cannot be accomplished by examining them in isolation.

Researchers from several academic fields have developed analytical frameworks to characterize and examine interactions between people and the environment. Many of these frameworks apply a systems perspective (e.g. Schlüter et al. 2012; Liu et al. 2015). A system is a connection of individual components that together produce results unobtainable by the components alone (Sage and Rouse 2009). Systems, then, are more than the sum of their parts (Bar-Yam 1997). Systems relevant to sustainability are often complex adaptive systems, and include multiple feedbacks, time delays, and nonlinearities. The important dynamics for many of these systems are poorly understood and inadequately conceptualized (Sterman 2011; Levin et al. 2013). To foster a better understanding of complexity, and thus to facilitate the design of new policies and catalyze change in support of sustainable development, John D. Sterman (2011, 21) has called for the launch of a new "systems science of sustainability."

In this chapter, we outline an analytical framework that we refer to as the HTE framework, using the perspective of a human-technical-environmental system coupled with a matrix-based approach. Our framework is designed so that readers from different backgrounds can use a common language and structure to identify and examine systems of relevance to sustainability, without prioritizing the terminology and concepts used by any one particular discipline. We apply our framework to examine five individual mercury systems in part II. The application of the HTE framework involves four steps, following our four research questions from chapter 1: first, cataloging system components; second, mapping interactions among the system components in an interactions matrix; third, identifying past interventions into system components and interactions using an intervention matrix; and fourth, drawing insights from the system analysis. For the fourth step, we identify three thematic areas for further discussion: systems analysis for sustainability; sustainability definitions and transitions; and sustainability governance.

A Matrix-Based Approach to Analyzing Human-Technical-Environmental Systems

For the first three of the four analytical steps in the HTE framework, we apply a matrix-based approach. Under the three subheadings below, we describe these steps—identifying system components, tracing interactions, and identifying interventions—and explain our matrix-based approach using the example of Minamata disease from chapter 1 and with the help of illustrative figures. The components identified in step one are used to build matrices for further analysis of interactions and interventions in steps two and three. These three steps address our first three research questions, respectively: (1) What are the main components of systems relevant to sustainability?; (2) In what ways do the components of these systems interact?; and (3) How can actors intervene in these systems to effect change? In chapter 8, based on our analysis of the mercury systems in part II, we synthesize results related to the matrix-based approach.

Components: Building Blocks of a System

The first analytical step is to identify the most important components for understanding system operations and dynamics. Analyzing a problem from a systems perspective requires deciding which components to include and which to leave out of the system description. Components are the elements or variables that exist within the boundaries of a defined system; system boundaries can be set at different geographical scales and can include or exclude specific sectors or topics. The identified components need to capture important system behavior, yet be few enough to allow for practical analysis. If everything is described as linking to everything else, identifying the system components and examining their interactions can quickly devolve into an intractable analytical problem, where the selection of overly broad system boundaries prevents the researcher from conducting a meaningful empirically grounded analysis. Because the most important components may change with time, a full description of a system may require a longer-term historical perspective.

When analyzing mercury, it is at least theoretically possible to include in a single system all the major components relating to its extraction, uses, discharges, exposure, and effects on the environment and human health, but such an approach would create a very large and difficult-to-analyze system structure. We therefore separate the mercury issue into five topical systems that correspond with major empirical issues and themes in mercury science and governance. Our selection of topical mercury systems is similar to the focus on an "action situation" within the Institutional Analysis Development framework developed by Elinor Ostrom and colleagues (Kiser and Ostrom 1982; Ostrom 2005; Ostrom 2011). Each topical mercury system has varying spatial and temporal dynamics. Some components are unique to each system, and some are common across two or more mercury systems.

We characterize systems of relevance to sustainability, such as the topical mercury systems, as comprising five different sets of components. Three sets are material, in the form of human, technical, and environmental components. The other two are the non-material institutional and knowledge components; they provide the context within which the human, technical, and environmental components interact. Each system component has a set of attributes that can be defined at a specific time, and many of these attributes change over time. Figure 2.1 shows how individual system components for the five mercury systems will be identified in each chapter in part II; we include in this figure a few illustrative components that are relevant to the Minamata story, which we discuss further below. We use an italicized typeface to emphasize the individual components from figure 2.1, and do the same when we describe each mercury system in its respective chapter.

Human components are people who live in different places and under different circumstances. Attributes of human components include social characteristics such as occupation, education, and level of income. Other attributes may be physical characteristics such as residence or location, or biological factors that influence health, including genetic conditions, age, and mercury levels in the body. People have different concentrations of mercury in their blood, hair, and urine as a result of their individual exposures. It is often analytically useful to consider individual humans as part of larger groups who share common characteristics and engage in similar behaviors. Using the Minamata story as an example, human components may include groups of people such as *factory workers* and *factory owners*. Other possible human components are fishers, pregnant women, children exposed in utero, and other categories of community members.

Technical components take the form of infrastructure and other material artifacts of human society. Collectively, these components have been

Human components	Technical components	Environmental components
Factory workers Factory owners …	Manufacturing technology …	Minamata Bay Fish …

Institutional components	Knowledge components
Markets National pollution laws …	Techniques for mercury use Health dangers of mercury …

Figure 2.1
Illustrative system components for the Minamata story.

referred to as the technosphere; the total physical mass of the current technosphere, including such things as buildings, roads, and consumer goods, has been estimated at approximately 30 trillion tonnes (note that throughout the book our use of "tonnes" refers to metric tons). This is about five times larger than the total mass of humans (Zalasiewicz et al. 2017). Attributes of technical components include their mass, quantity, performance characteristics, or concentration of mercury. Substantial quantities of mercury are present in a wide range of technical components; those related to the Minamata story include *manufacturing technology*, mercury used in chemicals production, and equipment that disposed of waste products. Other examples of technical components beyond the Minamata example include mercury in stocks and storage as a raw material, mercury in products such as light bulbs and batteries, pollution control technology, and landfills.

Environmental components consist of the Earth's life support systems and components of the biosphere—including all non-human living organisms in aquatic and terrestrial ecosystems. These range from large-scale systems, such as geological reservoirs, land biomes, the atmosphere, and the oceans, to more local systems such as rivers, lakes, forests, and coral reefs. Attributes of environmental components include physical properties such as wind speed, temperature, and depth, or biological information about organisms such as species, sex, or concentrations of mercury. Different forms of mercury are ubiquitous in environmental components, as they are found at different levels in ecosystems and wildlife in all regions of the world. Environmental components in the Minamata story include *Minamata Bay* as well as the *fish* and other aquatic organisms in which methylmercury accumulated. Mercury also travels long distances via environmental components as it cycles through air, water, and land on both shorter and longer time scales.

Institutional components are social structures outlining rules, norms, and shared expectations that define acceptable or legitimate behavior (Keohane 1989; Young 2002). As such, institutional components are distinct from actors such as international organizations, states, and other stakeholders (which we treat as potential interveners, discussed below). Institutions exist at local, national, regional, and global scales, and their specific rules, norms, and expectations may change over time. Some institutions set standards for human handling of (and exposure to) mercury. In addition, institutions mandate controls on emissions and releases of mercury to air, water, and land. Attributes of institutional components include their membership, scope, and stringency. In the Minamata story, *markets* facilitated the supply of mercury to the factory, but no domestic laws initially controlled the use of mercury in chemicals manufacturing. The outbreak of Minamata disease and other pollution problems, however, triggered the adoption of *national pollution laws*. Other institutions included the legal decisions holding Chisso responsible for releasing methylmercury into Minamata Bay and for providing compensation to Minamata disease victims.

Knowledge components incorporate information about human, technical, environmental, and institutional components and their connections. Attributes of knowledge components—related to specific locations and contexts—include awareness of, or the degree of certainty or uncertainty about, specific data and information. In the Minamata story, knowledge of *techniques for mercury use* influenced production in the Chisso factory. Knowledge of the *health dangers of mercury* and the fact that the disease was caused by methylmercury were unknown to local doctors and researchers until the relevant scientific information was identified and disseminated. The state of knowledge about how mercury affects human health can influence whether or not workers (human components) take safety measures when they handle mercury. Knowledge about the dangers of mercury can also influence uses of mercury in the industrial manufacturing of goods (technical components), the release of mercury into waterways (environmental components), and the formulation of pollution prevention standards and laws (institutional components).

Analysts may choose to define varying numbers of human, technical, environmental, institutional, and knowledge components within a system and at different levels of detail. The most appropriate level of detail for an individual component is largely an empirical question that is heavily influenced by the basic purpose of the system description and analysis. In the Minamata story, individual fishers can be identified as separate human components, or all fishers can be aggregated into a single human component for greater simplicity. Different types of mercury-using technologies can be distinguished as individual technical components, but they can be combined into one technical component if there is no analytical need to keep them separate. Environmental components can be individual species of fish, or all fish can be treated as a single component. Different national mercury laws can be identified as separate institutional components, or as just one collective component. Information about the toxicity of individual mercury compounds can be treated as separate knowledge components, or be aggregated into one.

The attributes of each of the five sets of system components convey information that helps to identify a component's location in time and space. Temporal attributes are defined with reference to a specific point in time, and could include the age of individual people (human components), infrastructure (technical components), and wildlife (environmental components) as well as the dates of laws (institutional components) and scientific discoveries (knowledge components). Spatial attributes can be measured relative to geographical distances or political boundaries on scales ranging from local to global. Some human components like Minamata fishers live within the same municipality, but others, such as commercial fish consumers, are spread across national jurisdictions and geographical regions. A technical component can be a pollution control device that is installed in a specific point source in a set location, or mercury that is traded across borders. An environmental component can be fish in a small lake or in a major ocean such as the Atlantic. An institution may be a law that applies only to a sub-national jurisdiction, or may be the global Minamata Convention. Knowledge about mercury's properties can be highly localized as well as diffused all over the world.

Our categories of system components illustrate that our concept of the HTE system is related to, but distinct from, other system descriptions, including social-ecological systems, social-environmental systems, coupled human-natural systems, human-environmental systems, socio-technical systems, production-consumption systems, and engineering systems (Liu et al. 2007; Ostrom 2009; de Weck et al. 2011; Markard et al. 2012; Selin and Friedman 2012; Levin et al. 2013; Chen 2015; Matson et al. 2016; Colding and Barthel 2019). These different system labels reflect a varying focus on distinct types of system components that are understood to interact in different ways. Each of these system descriptions emphasizes the importance of partially different components, but overlaps inevitably occur as components are conceptualized. In defining the human-technical-environmental system as used in this book, we aim to integrate and give equivalent attention to human-natural and socio-technical perspectives drawn from different literatures. We elaborate on further differences between the HTE framework and other system descriptions in chapter 8.

Interactions: Components Influence Each Other

The second analytical step uses a matrix as a heuristic tool to document and examine material interactions among human, technical, and environmental components, in the context of non-material institutions and knowledge components. The interaction matrix, as we call it, captures the behavior of the system as it changes through time. It documents which specific human, technical, and environmental components interact, how they do so, and the direction in which these interactions take place—that is, which material components influence others. The matrix format is useful to classify one-way as well as two-way interactions. In other literature, conceptual diagrams in which different aspects of systems are connected with boxes and arrows are commonly used to visualize human-natural or social-ecological interactions or networks (e.g., Ostrom 2009; Bodin et al. 2019). Matrices provide the same information as box-and-arrow or network diagrams, but it can be easier to visually compare interactions in different systems within a common matrix structure. Matrices are also used in the engineering systems literature to examine systems and their functions (de Weck et al. 2011; Eppinger and Browning 2012).

Interaction matrices can be presented in different ways. The illustrative matrix in figure 2.2 shows interactions that occur among the human, technical, and environmental components that we previously identified (following the first step of our analytical process) for the Minamata story in figure 2.1. We do not present a detailed matrix like this one in the individual chapters of part II, but we base our analysis in each chapter on such a detailed matrix. The existence of institutions and knowledge, as the non-material components that set the rules and parameters for material interactions, are indicated by large, shaded background rectangles. For purely illustrative purposes, figure 2.2 has four human components, eight technical components, and six environmental components. In the figure, these are indexed by the letters "i," "j," and "k," respectively. Each individual material component of the system occupies both a row and a corresponding column of the matrix. The matrix is read row first and column second.

A shaded cell in figure 2.2 indicates that the component in the row is influencing the component in the column. A shaded cell that lies along the diagonal shows a component interacting with itself. This represents a component's internal dynamics: for example, the deteriorating health of factory workers during the outbreak of Minamata disease (cell A). Interactions can

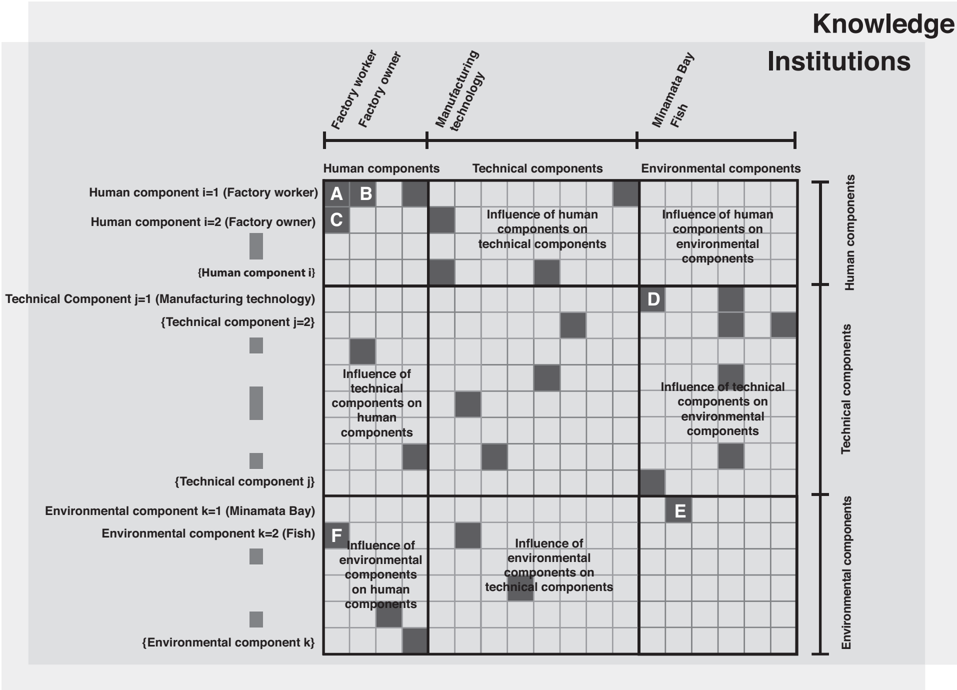

Figure 2.2
Illustrative matrix approach. The interaction matrix shows material interactions taking place in the context of institutions and knowledge. Shaded squares identify where interactions are occurring among material components.

occur between different components within the same set. The interaction between factory workers and factory owners, where workers provide labor to factory owners, is illustrated where the first row and second column intersect (cell B). The reciprocal interaction also occurs: factory owners provide wages to factory workers (cell C). Interactions can also take place between components from different sets. Manufacturing technology, a technical component, affects Minamata Bay, an environmental component, by releasing mercury into it (cell D). To illustrate what a more developed interaction matrix may look like, additional interactions within and across the same set of components are shown by the presence of other shaded but unlabeled cells.

Institutions include rules and other non-material structures that influence identified interactions among the human, technical, and environmental components, and the status of knowledge both facilitates and can reveal such interactions, as we discussed above. The detailed matrix in figure 2.2 identifies whether an interaction occurs among human, technical, and environmental components, and one or several institutional or knowledge components identified during the first analytical step may affect these interactions. For example, the interaction illustrated by cell D—whereby manufacturing technology releases methylmercury into Minamata Bay—is influenced by the existence of markets for both mercury and chemicals made from the mercury-based production process, and it may also be shaped by the adoption of a national law controlling the industrial use and environmental discharges of methylmercury. Access to knowledge about techniques for mercury use also affects whether the interaction in cell D occurs or not.

We trace interactions among human, technical, and environmental components through the matrix by identifying interaction pathways. We do this by first selecting a specific interaction to focus our analysis. We then identify the components that affect this interaction and those that in turn are affected by it. A simple interaction pathway involves cells B and C in figure 2.2, where a factory worker provides labor to a factory owner who in turn provides the worker with wages. In a longer pathway that can also be traced through figure 2.2, manufacturing technology releases mercury into Minamata Bay, illustrated in cell D. Minamata Bay then affects the fish by introducing methylmercury into the food web, illustrated by cell E. The fish in turn affect the factory workers who consume them and begin building up concentrations of methylmercury in their bodies, shown in cell F and cell A. This D-E-F-A pathway also connects to the earlier B-C pathway through the factory worker, and these two pathways could be considered together as one combined pathway if that is analytically useful.

Analysts can use the matrix approach to identify causal links among components by tracing pathways from a selected interaction either forward (to determine potential influences prospectively) or backward (to identify causal factors). In the pathway described in the previous paragraph, going forward from cell D to E to F in figure 2.2, causal links are traced across technological, environmental, and human components to identify how mercury discharges affect the environment and then people. If, in the same example, the purpose is to examine what led to the accumulation of methylmercury in factory workers, the pathway can be traced backward from cell F to E to D. This exercise would help identify the adoption of a local or national pollution law as a potential solution to the risks of methylmercury exposure in factory workers who eat contaminated fish (as well as to other consumers of fish from Minamata Bay).

Changes in the attributes of all five types of system components can provide information about spatial and temporal dynamics. These changes may occur in self-interactions (for example, the aging of populations and infrastructure) or via interactions with other components. Comparing the spatial attributes of the different interacting components in the Minamata story reveals that many interactions between material components were local. In cell D, the individual interaction occurred between a local point source, in the form of a manufacturing plant that discharges methylmercury, and Minamata Bay, which received this methylmercury locally. The methylmercury in Minamata Bay accumulated mainly in local fish (cell E), which in turn was consumed mostly by nearby populations (cell F). At the same time, many of the market-based interactions that involved buying and selling mercury (and the chemicals produced by the factory) were national and international. Knowledge about techniques for mercury use as well as the health dangers of mercury also diffused across international borders.

Using the matrix approach to trace interactions across temporal scales in the Minamata story shows that interactions among material components lasted for both longer and shorter periods of time. The chemical factory in Minamata used commercial mercury in two production processes and released methylmercury into Minamata Bay for several decades starting in the 1930s, and it took nearly 70 years after the methylmercury was first discharged from the factory to clean up Minamata Bay (cell D). Methylmercury discharged into Minamata Bay began to quickly accumulate in local fish as they grew and matured (cell E). After the discharges of methylmercury began, it took more than two decades before the local doctor identified the first patient who had contracted Minamata disease from eating contaminated fish (cell F). Although many fishers and other people died a few years after contracting Minamata disease, some people who suffered irreparable damages to their nervous systems were alive and still affected by Minamata disease well into the early decades of the twenty-first century.

We have taken the illustrative interactions among human, technical, and environmental components related to the Minamata story from figure 2.2, described them in qualitative terms, and aggregated them in their respective sets in figure 2.3, which appears below. In part II, we present interaction matrices in the format of figure 2.3, using mainly qualitative data, as

Knowledge
Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1) Factory owners employ factory workers	(1-2)	(1-3)
2. Technical	(2-1)	(2-2)	(2-3) Manufacturing technology releases methylmercury into Minamata Bay
3. Environmental	(3-1) **Fish contaminated with methylmercury cause health damages to fish consumers**	(3-2)	(3-3) Minamata Bay fish bioaccumulate methylmercury

Figure 2.3
Illustrative interaction matrix for the Minamata story.

we examine interactions and provide system-level insights for the mercury systems discussed in each chapter. This allows us to present necessary context and detail for the respective interactions. If sufficient quantitative data were available, and if it were analytically feasible and appropriate, it would be possible to construct a quantitative model. A quantitative model based on the Minamata story could simulate mercury in the fish in Minamata Bay and in the bodies of the people who consume that fish. The interaction matrix could then be used to calculate and describe the rate of change at which mercury builds up in the fish, as well as the rates at which mercury accumulates in (and discharges from) human bodies over time. This calculation is similar to what is known as a first derivative, which identifies whether a mathematical function is increasing or decreasing, as well as its instantaneous rate of change.

The diagonal boxes of figure 2.3 (e.g., boxes 1-1, 2-2, and 3-3) represent interactions among material components in the same set, including where an individual component interacts with itself (the diagonal cells in figure 2.2). The boxes that do not fall along the diagonal represent interactions that involve different sets of material components, where the first number indicates the row and the second number indicates the column of the aggregated matrix (box 1-2, etc.). For example, as noted above in figure 2.2, manufacturing technology affects Minamata Bay in cell D. In figure 2.3, we describe this in general terms as "manufacturing technology releases methylmercury to Minamata Bay" in box 2-3.

Our choice to identify a few particular interactions to focus our analysis for each topical system in part II is based on their prevalence and/or their importance to human well-being. We then trace the pathways that involve those interactions through the matrix. For the Minamata story, we might have chosen to focus on the interaction in cell F, identified by bolded text in box 3-1 in figure 2.3, where fish contaminated with methylmercury cause health damages to fish consumers. We could then analyze the pathway from cell D to E to F, in which pollutant discharges affect ecosystems and ultimately factory workers, by identifying and discussing the pathway in which manufacturing technology releases methylmercury to Minamata Bay (box 2-3), the Minamata Bay fish bioaccumulate methylmercury (box 3-3), and the methylmercury-contaminated fish in Minamata Bay subsequently cause health damages to fish consumers (box 3-1).

In the system interaction section of each chapter in part II, we illustrate how interactions form pathways using box-and-arrow diagrams as shown in figure 2.4. We discuss each identified pathway in greater detail in narrative form. It is important to note that the boxes in these pathway diagrams represent the interactions, and thus capture the way in which two material components influence each other, while the arrows connect two interactions that involve the same individual component. That is, the first arrow in figure 2.4 connects the interaction where manufacturing technology affects Minamata Bay (by releasing methylmercury into it) with the interaction where Minamata Bay affects the fish. The second arrow further connects the interaction in which Minamata Bay affects the fish (by causing methylmercury accumulation) with the interaction where that fish causes health damages to fish consumers. Thus, these diagrams are different from other box-and-arrow diagrams in which boxes

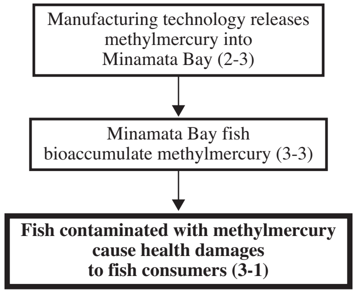

Figure 2.4
Illustrative box-and-arrow diagram for the Minamata story (pathway D-E-F from figure 2.2).

would indicate components and arrows would capture causal connections in the form of interactions.

Interventions: Actors Changing System Interactions

The third analytical step is to identify interveners—the actors who have agency to modify a system—and examine past interventions that have changed the ways material components function and interact. Interveners in the mercury systems include those who use mercury, those who are affected by mercury, those who develop new technology, and those who are engaged in mercury governance. Sometimes these are individuals, including business owners, workers, consumers, researchers, public officials, and members of the general public. In addition, groups of individuals operate in collective entities, such as networks, organizations, and governments, and act across public, private, and civil society sectors. Individuals and groups of actors engage with mercury issues in different ways from local to global levels. Interveners in the Minamata story include doctors and local and national governments. Interveners have differing levels of power and influence, which we evaluate by assessing the degree to which they are able to effect change within a system.

To examine how interveners can influence system interactions by adding or subtracting components or changing their attributes, we use an intervention matrix in every chapter of part II, similar to the one in figure 2.5. We construct the intervention matrix by identifying the components and interactions that the intervener targets, and then describing the intervention in the box that it relates to. In figure 2.5, where we list local and

Knowledge
Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1)	(1-2)	(1-3)
2. Technical	(2-1)	(2-2)	(2-3) National government creates new pollution laws
3. Environmental	(3-1) National government sets methylmercury limits for fish sales and consumption; Doctors share knowledge about health damages	(3-2)	(3-3) Local government cleans up Minamata Bay

Interveners
Local and national governments; Doctors

Figure 2.5
Illustrative intervention matrix for Minamata.

national governments and doctors as examples of interveners in Minamata, box 2-3 represents how the Japanese national government tried to prevent future damage associated with environmental releases by creating new pollution laws. The local government also cleaned up Minamata Bay, thereby changing how ecosystem components interact with each other (box 3-3). In addition, the national government set methylmercury limits for fish sales and consumption and doctors shared knowledge about health damages (box 3-1) to prevent people from eating fish contaminated with methylmercury.

The intervention matrices in part II identify the main interveners and interventions that have directly or indirectly modified mercury-related interactions among human, technical, and environmental components of each mercury system. We examine interveners and interventions that resulted in changes in levels of mercury discharge or mercury use in particular applications, as well as those that involved initiatives to protect human health and the environment from mercury exposure and pollution (including, but not limited to, national laws and the Minamata Convention). We identify these interveners and interventions through an analysis of the empirical material, building on the previous matrix-based examination of system components and interactions.

Distinguishing interactions from interventions depends on the moment in time that a system is analyzed. Some interactions can be affected by past interventions. In the Minamata story, for instance, no national pollution law existed when Chisso began to discharge methylmercury into Minamata Bay. The subsequent passage of such a law was an intervention that changed the way system components interacted. An examination of the present-day Minamata system would treat the national pollution law as an existing institutional component. Our analysis in part II takes a historical perspective, so we do not explicitly identify a moment in time at which the interaction and intervention matrices are constructed. We choose to do this for clarity—presenting a separate set of system components and related interaction and intervention matrices for multiple points in time for each mercury system would make the system presentations and discussions exceedingly complex. This means, however, that in part II there is some overlap between what we discuss as an interaction and what we treat as an intervention. In the interventions sections, we identify interventions that we believe are most relevant to understand and learn from with respect to sustainability.

We describe the interventions summarized in figure 2.5 qualitatively (as we do for all the interventions we discuss in part II). This is similar to the way we analyze interactions. The intervention matrix can also be used as a basis for quantitative systems modeling—just like the interaction matrix can—if the necessary data are available. In such an approach, where the interaction matrix quantifies the rate at which system attributes change through time, the intervention matrix would describe alterations in that rate. A quantitative intervention matrix might be used to calculate how quickly the accumulation of mercury would change, not only in fish in Minamata Bay but also in the people who eat that fish, once the factory stops releasing any more methylmercury. This corresponds in mathematical terms to a type of second derivative. Analysis of a second derivative matrix can reveal characteristic timescales and identify whether a system exhibits small or large, or stable or unstable, responses to perturbations.

Insights: Lessons about Sustainability

The fourth analytical step, related to our fourth research question (What insights can be drawn from analyzing these systems?), looks across the components and matrices to synthesize insights about how the mercury systems have operated in a broader context of sustainability. We chose three thematic areas to help guide readers from different disciplines toward insights particularly relevant to the types of questions that interest them, and we present these as separate sections in each chapter in part II. First, in the sections titled "Systems Analysis for Sustainability," we focus on insights relevant to those who study environmental or engineered systems and complex adaptive systems more generally. Second, in the sections titled "Sustainability Definitions and Transitions," we center on issues of concern to researchers interested not only in concepts of sustainability but also in how societies can move toward greater sustainability. Third, in the sections titled "Sustainability Governance," we address topics that are of particular interest to scholars who study policy-making and the role of institutions. Following our analysis of the mercury systems in part II, we return to these thematic areas in chapter 9.

Systems Analysis for Sustainability

Many researchers increasingly acknowledge that systems perspectives are necessary to describe and analyze environmental processes influenced by humans. These include those who study mercury and its environmental behavior. Biogeochemical cycle analyses quantify how mercury and other elements such as carbon and nitrogen move and change forms through biological systems, geological processes, and chemical reactions, and quantify their disruptions due to human activities (Klee and Graedel 2004). Other systems research aims to trace the flow of materials such as minerals or fossil fuels through societies, economies, and regions (Erkman 1997;

Fischer-Kowalski et al. 2011). A growing community frames its research as Earth system science, where human activities are seen as a fundamental part of Earth systems (Reid et al. 2010). Some researchers focus on understanding interactions as part of coupled human and natural systems (Liu et al. 2007), or integrated social-ecological systems (Berkes 2017). In addition, some engineering systems literature treats sustainability as a design problem, and researchers work to develop better methods to guide design decisions (Cutcher-Gershenfeld et al. 2004).

Systems research relevant to sustainability often focuses on understanding the properties and behavior of complex adaptive systems. The components of any system have individual attributes such as those we described earlier for human, technical, environmental, institutional, and knowledge components. The system itself may have further properties that are more than the sum of its parts. For example, each fish in a school has its own individual position and velocity, but the shape of the entire school of fish is a property of the system as a whole—the fish swimming together—and is not predictable from individual fish motions. System-level characteristics that emerge from interactions among system components are sometimes referred to as the emergent properties of a complex system (Johnson 2006). Systems relevant to sustainability are also typically adaptive—the patterns that emerge from system interactions may feed back and influence future interactions (Holland 2006; Levin et al. 2013).

Previous work suggests that a particularly important system-level emergent property involves the degree to which systems can change and remain functional when they experience shocks or perturbations (Ross et al. 2007). This is sometimes referred to as a system's adaptive capacity (Smit and Wandel 2006). Similarly, resilience is seen as the capacity of a system to absorb a disturbance and reorganize while retaining its function and structure (Walker et al. 2004; Folke 2016). Adaptation can occur over shorter and longer timescales, and may involve advances in knowledge and innovations in technology and institutions. Whereas the early resilience literature, with its roots in ecology, focused on the behavior of ecosystems (Holling 1973), later analysts have also applied the resilience concept to social systems (Adger 2000; Hall and Lamont 2013). Resilience in this context has been described as the capacity for social-ecological systems to sustain the desired benefits humans gain from ecosystems in the face of disturbances and changes (Biggs et al. 2012).

Much research on complex adaptive systems related to sustainability is shaped by the fact that humans have become a dominating force at planetary scale, as captured in the concept of the Anthropocene. Debates about whether the Anthropocene concept is useful involve controversies over selecting an appropriate start date for this potentially new epoch. This is related to the task of identifying changes in a system's state—in this case, when people became an important driver of changes in the Earth system. For some Earth system processes, changes may be fairly linear toward a threshold, but others can be nonlinear and involve tipping points in the Earth's life support systems (Lenton et al. 2008). Some researchers have argued that crossing certain planetary-scale boundaries, in areas such as biodiversity loss or climate change, can have detrimental or even catastrophic consequences for humanity (Rockström 2009; Rockström et al. 2009). Others have criticized the planetary boundaries idea as a poor basis for conceptualizing environmental challenges (Nordhaus et al. 2012). Chemicals pollution at the global scale is one area in which researchers have nevertheless applied the planetary boundary concept to help assess disruptive effects on vital Earth systems (MacLeod et al. 2014).

Analyzing the mercury systems provides insights both for those who study mercury and for systems analysis more generally. For those who are interested in better tracing how mercury travels through the environment and society, examining the mercury systems can reveal components and processes that are often overlooked in disciplinary analysis, help identify causes of observed changes, or suggest levers for mitigating harms posed by mercury to human health and the environment. For systems analysts, mercury provides an empirical case from which to draw further insights into system operations. Engineering systems researchers may ask how environmental components impact efforts to study socio-technical dynamics. Those interested in adaptation and resilience may consider whether and how resilience thinking can be applied to the management of pollutants. For scientists interested in systems approaches to planetary-scale environmental processes, mercury offers a test of the utility of related perspectives and concepts such as the Anthropocene or planetary boundaries.

Sustainability Definitions and Transitions

The academic literature contains several different definitions of sustainability. Some analysts define sustainability in terms of maintaining natural resources at a level that does not exceed their ability to be renewed (Daly 1990). This idea, resting on the foundation that there are no substitutes for some forms of natural resources, is sometimes referred to as "strong" sustainability (Neumayer 2003). Another definition of sustainability allows for depleting natural resources as long as other resources that maintain human well-being can substitute for them in the longer term. From this perspective, it is consistent with sustainability to deplete a non-renewable resource to a certain extent, provided that other investments can compensate for its functions. Applying this idea, however, requires understanding how such tradeoffs are valued both in theory and in practice. This idea is reflected in literature that assesses whether fundamental stocks of capital that human well-being depends on—natural capital as well as other types such as manufactured and human capital—are maintained through time (Polasky et al. 2015).

Analysts apply different perspectives on how societies can make progress toward sustainability. From the perspective of ecological modernization, environmental protection and economic growth are regarded as mutually supportive, and the development of new and more environmentally friendly technology is seen as critical to making progress on sustainability (Spaargaren and Mol 1992; Mol 2003). This perspective emphasizes that contemporary societies can be "greened" through new technology without fundamentally changing the basic principles of production, consumption, and trade that are embedded in contemporary capitalism (Neumayer 2003; Meadowcroft 2012; Bulkeley et al. 2013). In addition, the idea of a circular economy suggests that improved recycling and reuse within the existing economy, with the ultimate goal of a closed-loop system, can contribute to greater sustainability (Ghisellini et al. 2016). However, some analysts argue that progress toward sustainability requires much more profound changes in human consciousness and behavior, together with deep alterations to dominant production, consumption, and trade patterns (Princen 2005; Speth 2008; Dryzek 2013).

A growing number of analysts focus on better understanding past and present sustainability transitions, often with an eye toward supporting future transitions (Markard et al. 2012; Feola 2015; Loorbach et al. 2017). Some of these analysts make a conceptual distinction between transitions and transformations (Pelling 2010; Linnér and Wibeck 2019). A transition is seen by these analysts as involving a largely incremental and step-wise change process away from the status quo. In contrast, they view a transformation as a more fundamental and wide-ranging departure from business as usual toward something intrinsically different. Yet, authors in the transition and transformation literature are not consistent in their definition and use of the two terms (Patterson et al. 2017). Both terms—“transition” and “transformation”—nevertheless embody the basic idea that different forms of change are necessary for societies to move to a more sustainable trajectory. We use “transition” as an umbrella term to describe multidimensional change processes to a more sustainable state, as other researchers have done previously (e.g., Markard et al. 2012; Loorbach et al. 2012).

Our analysis of the mercury systems contributes to debates on sustainability concepts and transitions in several ways. We chose in this book to define sustainability, as noted in chapter 1, as centered on human well-being. Those who focus on different ways to define sustainability can use the case of mercury to ask whether any use of mercury could ever have been considered sustainable, and under what conditions. Those who apply ideas like ecological modernization or the circular economy can draw insights from trends in mercury use and discharges over time. For analysts who are interested in better understanding and informing sustainability transitions, the long history of human interactions with mercury offers empirically rich information, focusing on an issue that involves humans, technology, and the environment simultaneously. Analysts who focus on transitions may be particularly interested in the interacting temporal and spatial dynamics of change processes in the mercury systems, where immediate impacts occur simultaneously with much longer, remote feedbacks.

Sustainability Governance

Governance for sustainability requires simultaneously addressing many socio-economic, technical, and environmental issues. Governance structures involving one or multiple institutions can be seen as complex systems that have their own thresholds and tipping points (Young 2017). These institutions are created through collective action, and in turn many of their formal and informal rules shape human activities in a process of mutual co-construction. Governance for greater sustainability requires both reformed and new institutions and networks that can meet governance challenges on a human-dominated planet (Biermann 2014). These can be created through top-down and bottom-up change processes. Governments play many central roles in sustainability governance: they are the negotiators and implementers of international environmental agreements like the Minamata

Convention, and they have the ability to pass domestic legally binding rules and standards. International organizations, private sector actors, market participants, civil society organizations, and individuals also shape governance in a variety of ways.

Many current international and domestic legal, political, and economic institutions are largely ill equipped and inadequate to manage a transition toward greater sustainability (Biermann et al. 2012). This is in part due to a frequent lack of match—or fit—between the scope of these institutions and the biophysical and socio-economic systems that they are designed to govern (Young 2002; Folke et al. 2007; Epstein et al. 2015). A major strand of the governance literature focuses on how to design new and modified institutions to more effectively address sustainability problems, often centering on the importance of paying careful attention to the underlying physical characteristics of the problems that they address (Mitchell 2006). Some of this literature stresses that polycentric and multilayered institutions can improve the fit between institutional scope and properties of biophysical and socio-economic systems (Young 2002). These types of institutions also allow for a large number of actors (including possible interveners) to be involved in different forums and across governance scales.

Social scientists view governance as an inherently social process, whereby actors intentionally seek to steer individuals, groups, and societies toward a collective outcome, such as greater sustainability. Stakeholders may have very different views on how to do that, and even on how to define sustainability. These views are shaped by many political, economic, social, cultural, and environmental factors. In addressing mercury and other sustainability issues, societies have to make normative decisions among a multitude of possible transition pathways as part of any governance process (Meadowcroft 2011; Patterson et al. 2017). The importance of stakeholder involvement in describing a sustainability problem, and identifying and dealing with trade-offs of different options for addressing that problem, is stressed in the sustainability science and governance literatures (Brandt et al. 2013). The importance of broad participation in sustainability governance is also related to issues of equity and justice, as different stakeholders may have very different levels of influence and power in shaping decisions that affect societies and, ultimately, the planet.

Analysts of governance and policy-making processes, and practitioners who are engaged in the creation and implementation of domestic laws and standards or international institutions like the Minamata Convention, will find in part II many examples of how efforts to govern different aspects of the mercury issue evolved over time, with many intended as well as unintended results for human well-being. Those who are interested in how to design more effective revised or new governance structures may be particularly interested in how institutions fit with different material components and characteristics of the mercury systems. The overlapping nature of mercury governance at multiple geographical scales also offers a comparative perspective on how local, national, regional, and global efforts and institutions addressed multifaceted mercury issues of much importance to human well-being. In addition, governance scholars may be interested in linkages between mercury and other sustainability issues.

The HTE framework that we introduce in this chapter forms the structure for examining the topical mercury systems in the five chapters of part II. These chapters are organized based on a common four-step approach associated with the book's four research questions. First, they describe the human, technical, environmental, institutional, and knowledge components (research question 1). Second, they examine interactions between components (research question 2). Third, they look at system interventions focused on sustainability (research question 3). Fourth, they draw insights relevant to the three areas of systems analysis for sustainability, sustainability definitions and transitions, and sustainability governance (research question 4). In the three chapters in part III, we synthesize this empirical material. Chapter 8 returns to the first three research questions, whereas chapter 9 addresses research question 4. Chapter 10 concludes the book by drawing lessons for future efforts to further address the mercury problem, targeted toward researchers, decision-makers, and thoughtful citizens.