SYSTEM BEHAVIOR AND SYSTEM MODELING

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INTRODUCTION
What Is a System?

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System science is not a new idea, but it is receiving renewed attention today because many of the global problems facing humanity are complex ones that transcend the classical disciplinary boundaries between and within the natural and social sciences. System science provides a methodology for quantitatively describing the behavior of complex dynamic systems. Because of this, and because of the broad applicability of system science and the increasing numbers of global problems requiring interdisciplinary skills, system science will continue to increase in importance in all disciplines. The purpose of this Global Change Instruction Program (GCIP) module, *System Behavior and System Modeling*, is to introduce system behavior, system science methodology, and system modeling.

A system may be very simple, such as a bathtub full of water, or very complex, such as the Earth's climate system or the solar system. It may be entirely physical; it may be social, such as a political system; or it may include both human and physical components. Ultimately, the system under consideration in Earth system science is the entire universe; from this system we isolate and define a much smaller subsystem that we hope to understand.

The first step in defining a system is to identify its components and interactions, if any, with other systems. Some of the components may themselves be systems, making them subsystems of the larger system. If a system has no significant interactions with the outside universe, we call it an isolated system. The second step is to identify the interactions between the components within the system.

The process of defining a system can be approached on a qualitative or quantitative level. When we provide a quantitative description of a system we call it system modeling. The qualitative system description can also be very useful in identifying system components and interactions that are important to understanding and altering the system's behavior. Consider carbon dioxide in the Earth's atmosphere. The system will include atmospheric carbon dioxide, energy production from fossil fuels (which give off carbon dioxide when burned), and complex subsystems of human energy consumption, fossil fuel recovery and marketing, fossil fuel reserves, human cultural and sociopolitical factors, as well as the subsystem associated with conservation and development and marketing of alternate energy sources.

There are important interactions among the system components. Measurements reveal a steady annual increase in atmospheric carbon dioxide produced primarily by the burning of fossil fuels to produce energy. Total energy use depends upon two things: the human population and the per capita energy use. (In a quantitative system model we could break this down by nation or groups of nations with similar energy-use patterns.) The per capita energy use is influenced by lifestyle, income, fuel availability, fuel cost, and available alternatives. Lifestyle includes factors like personal transportation, house size, heating and cooling requirements, urban or rural environment, and conservation practices. This system that we have just defined is not an isolated system because we included only the carbon dioxide in the air, not the carbon in the oceans or living things, which absorb carbon dioxide from the atmosphere.

What happens if the population steadily increases and the per capita energy use remains constant? Atmospheric carbon dioxide continues its increase. What if the population is stabilized but the per capita income increases? Atmospheric carbon dioxide continues its increase. If we wish to stop the increase in atmospheric carbon dioxide, which of the system or subsystem components that we have identified can we realistically control? Population, fuel cost, available alternatives, and conservation practices are good choices.

In the long term one of the system components listed above will ultimately dominate the system behavior: fuel availability, because fossil fuel is a finite resource. But before we reach that point, the accumulating atmospheric carbon dioxide and its associated global warming may produce unwanted and harmful effects on the larger Earth system. In order to know what these effects may be, we need to be more detailed and complete in defining our system and quantitative in including the interactions within and between the systems. This will require a system model.

Exercise

In the discussion of qualitative modeling we briefly described a system relating human use of energy to the increase in atmospheric carbon dioxide. The purpose of this exercise is to build upon this system and examine the interactions in greater detail. Step-by-step procedures for completing it are below. The exercise does not have a unique correct answer, but your response should be internally consistent, reflect known system relationships, and include all of the important items and interactions.

Use an outline format to define the basic structure of this system; the major, first-level, outline items will list the important components and subsystems of the system, and the next level of the outline will list the components of the subsystems. You may add components and subsystems beyond those discussed in the text, and you may even add subsystems to subsystems if you think it is necessary. You may use the simplified outline provided below or build your own system outline on it.

Now characterize each item in your outline as positive, + (increases in the item increase atmospheric carbon dioxide), or negative, – (increases in the item work to decrease atmospheric carbon dioxide). For example, "Human Population" is positive while "Fuel Taxes" is negative. You may find it helpful to add, delete, and redefine the items in your outline; if you have an acute shortage of negative items, you may need to add new items such as "Birth Control Practices" or "Energy Policy" at the appropriate place in the outline. In the simple system outline below these items are italicized to remind us that they are not fully in place and operational. Some major outline items will have both positive and negative subitems; in this case, indicate "+ or -" for the major outline item, or give it the sign of the most influential of its subitems.

Next show the interactions between the items on your outline with arrows. For example, you should have arrows from "Fossil Fuels" to "Atmospheric Carbon Dioxide" and from "Standard of Living" to "Per Capita Energy Use." All components of a subsystem implicitly interact with the subsystem itself; they need not be shown with arrows. Interactions from the hypothesized items should be shown with dashed-line arrows to indicate their provisional nature. As you complete this part of the exercise you may discover that there is a better sequence for your outline so that most of the arrows point up the outline to form a chain of interactions with "Atmospheric Carbon Dioxide" at the top. Try to show all of the interactions with a minimum number of arrows; you may want to eliminate the arrows without a clear purpose.

Now label each of the arrows with either an

"S" to indicate a strong interaction or a "W" to indicate a weak interaction. The "Fossil Fuels" to "Atmospheric Carbon Dioxide" link is strong because the energy production directly produces carbon dioxide, which is directly injected into the atmosphere. The "Influence and Persuasion" to "Conservation, Nuclear, or Alternative Energies" connection is weak because the interaction is voluntary and depends upon relative prices of energy and the capital investment required to convert to different energy sources.

Now trace the sequence of arrows leading from each of the negative items in your outline to "Atmospheric Carbon Dioxide" and characterize the strength of the complete connection by the weakest link in the chain. Finally, list by priority (strength of the interaction chain) the items that can work toward reducing the increase in atmospheric carbon dioxide. Identify the high-priority items from the "Cultural, Social, and Political Influences" subsystem. How many strong interactions are currently active?

SIMPLIFIED SYSTEM OUTLINE FOR HUMAN INFLUENCE ON ATMOSPHERIC CARBON DIOXIDE

1. **Atmospheric Carbon Dioxide**
2. **Energy Production**
   - 2.1. Fossil Fuels
   - 2.2. Conservation, Nuclear, or Alternative Energies
3. **Human Energy Needs and Uses**
   - 3.1. Human Population
   - 3.2. Per Capita Energy Use
4. **Fossil Fuel Market = Price**
   - 4.1. Fuel Taxes
   - 4.2. Owned Reserves
   - 4.3. Imported Reserves
   - 4.4. Public Reserves
5. **Cultural, Social, and Political Influences**
   - 5.1. Standard of Living
   - 5.2. *Birth Control Practices*
   - 5.3. *Energy Policy*
   - 5.4. Influence and Persuasion

Discussion

We started with some vague ideas of how this system worked, and by imposing structure on them we have refined our understanding of the system. This activity probably confirmed some of our prior opinions and focused our thoughts on the interactions and the differences in the importance of various strategies in interacting systems. As we progressed from our initial, almost subjective, opinion of how this system works to a nearly quantitative diagram, we have gained confidence in our understanding of the system, and perhaps we have changed some of our opinions.

Imagine the next step in the process that we started above. Suppose that we assign a number between 1.0 and 0.0 to each of the interacting arrows in place of the "S" or "W," where 1.0 is the strongest interaction possible and 0.0 is no interaction at all. We can compute a number for each complete interaction chain by taking the product of all of the values in the chain. The resulting number represents the strength of the item in influencing the ultimate objective, such as reducing atmospheric carbon dioxide. This semi-quantitative approach assists in establishing priorities and in evaluating which, and how much, "negative" action is required to counteract a specific "positive" action. The final improvement in understanding the system is to make a dynamic model of it that can change with time so that the system can respond to changing conditions.

A few of the items in the outline require explanation. The fossil fuel reserves, 4.2–4.4, are separated into three types—owned, imported, and public—which correspond respectively to those that are owned by the energy producer or a private party who sells to the producer; imported by the energy producer; and public, such as those on nationally owned lands or offshore in national territory. We separate the three reserves because the energy producer uses a mix of them to keep the price of fossil fuel products low and because energy policy can interact with the three reserves in different ways. It should not be a surprise that if the only reserves available to an energy producer were the owned reserves, their value would quickly escalate.