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.

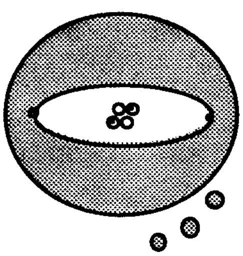
A few of the items in the outline require explanation. The fossil fuel reserves, 4.2–4.4, are separated into three types—owned, imported, and public—which correspond respectively to those that are owned by the energy producer or a private party who sells to the producer; imported by the energy producer; 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.

I
What Is Modeling?

Conceptual Modeling

The mind forms a visual image of an object, system, or process.

Modeling is really something we do every day. We form a conceptual model of some object, system, or process by creating a mental image of it. The mental image is a model, and the activity of creating the mental image is modeling. Consider the word "atom." Your mind has probably conjured up a picture that is your model of an atom. Perhaps you see a central body made up of black and white spheres representing protons and neutrons packed closely together, and around this central body fly tiny black dots in orbits, the electrons. (Modern physics tells us that this is not the best description for an atom, but this simple picture is the starting model from which physicists build the more complex models of quantum physics.)



Communicating with Models

System behavior can be communicated with stylized drawings.

Have you noticed the widespread use today of icons, visual symbols often used to direct public behavior? A modern icon is a highly stylized model of an object or process (behavior). This international use of icons began when Volkswagen needed a universal language to communicate "headlights" and "windshield wipers" to the world's drivers. The use of graphics for communication has continued to expand as more products are marketed internationally. And, as more people travel internationally, there is an increasing need for highway and pedestrian signs that are language-free. In recent years we have seen the beginning of a revolution in the computer world, as icons replace the command languages that have for years dominated the human-computer interface. By using icons we can communicate mind-model to mind-model without translating our meaning through two languages.

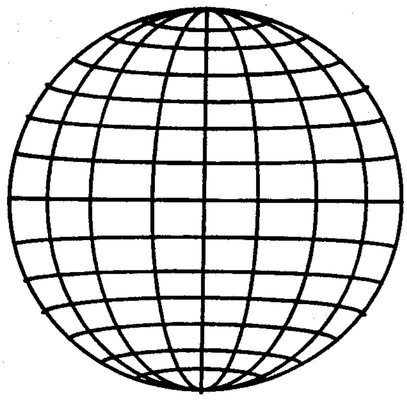
The use of stylized drawings to depict the elements in a system and our understanding of how they interact has proven to be as valuable to the person modeling a system as the use of icons is to the international manufacturer. In addition to avoiding language problems, the use of system model diagrams is a more precise method of describing exactly what you, the model builder, have in mind.

Computer Models

Computers are used to model systems that are too complex to distill into a single statement or equation.

Creating numerical computer models of complex systems has become the most important application for large computers in science. In fact, it is problems like modeling the weather, climate, and location of fossil fuel reserves that are driving the computer industry to build larger and faster supercomputers. Although the supercomputers are necessary for complex, global models, smaller computers, even personal computers, also have an important role in the whole range of computer modeling.

What forces a model to require a large computer is usually spatial and temporal resolution. How detailed a picture, in space and time, does it provide? A weather forecast model that cannot portray the local weather in New York, Houston, and Seattle would have very limited usefulness; hence, a weather forecast model must have high spatial resolution. In an hour following sunrise, the surface temperature can increase several degrees. A weather forecast must have high temporal resolution to follow these changes or it cannot correctly portray the science that is occurring. For forecasting purposes, the Earth's surface is divided into many contiguous areas and the atmosphere above these areas is divided into layers; the volume elements formed by this process are called cells. The objective of weather and climate models is to forecast all of the atmospheric variables in all of the global cells for each specific time in the forecast period—the more times, the higher the temporal resolution.



Experience with large models has shown that the computational power requirements (computer memory size and arithmetic speed) are roughly proportional to the cube (power of three) of the number of cells in the model. Climate modelers would like to have global models with ten times better resolution than the models currently running on the world's most powerful computers; to fill this need, computing technology needs to be improved by a factor of a thousand!

Fortunately, for our purposes in this module we usually don't require high spatial or temporal resolution. In examining factors like global mean temperature and atmospheric CO_2 concentration, treating the Earth as a unit is adequate.

Exercises

1. The word model has many uses: a person that exhibits clothing, a miniature replica of an aircraft, exemplary behavior (as in a "model Boy Scout"), making three-dimensional objects from clay, etc. It has noun, adjective, and verb forms. Look up "model" in an unabridged dictionary to see the full breadth of this word. Why should it have such broad application? The answer is in the underlying meaning of the word: the visual image that is formed to represent the real object. Write two sentences employing "model" in each of its forms: noun, verb, and adjective (six sentences total). Write sentences that show the diverse uses of the word "model."

2. Suppose the size of a cell in a global model is to be 100 km by 100 km in the horizontal and divides the atmosphere into 15 layers. How many cells are required in the global model?

II
The Perspectives Provided by Modeling

Forecasting the Future

Models based upon understanding present system behavior are used to forecast the future.

Modeling is often used to forecast the future. This type of modeling occurs at every level of human activity from subconscious thinking to supercomputer modeling. You are actually using a conceptual model when you deal with the question, "Do I need to buy more milk?" Some of the procedures you use in responding to this question are (1) to check the level of the milk in the refrigerator; (2) to recall the rate at which the milk is being consumed in the household; (3) to predict how long the present supply will last; (4) to decide if the milk supply will last until the next shopping time. You have become so adept at modeling at this level that you probably have never thought about all of the steps that your mind takes to make this decision.

At the supercomputer level good examples of future forecast models are at the National Center for Atmospheric Research in Boulder, Colorado, and at the Goddard Institute for Space Studies in New York City. These groups use general circulation models (GCMs) to obtain moderate-resolution global forecasts of future climate conditions at the regional spatial level and the seasonal temporal level. GCMs provide detailed information including regional temperature, pressure, wind velocity, humidity, cloudiness, precipitation, and other derived parameters. (The GCMs are also called three-dimensional models because they treat latitude, longitude, and altitude as independent spatial variables.)

Most climate modelers agree that the climate models are not very accurate at the regional level because the cells used in them are typically 500 km on a side, about the area of the state of Colorado. This entire area must be represented by a single altitude, a single temperature, etc. In the real world there are large variations in all climate variables inside a cell of this size; there is no hope of correctly depicting regional conditions with such models.

The large computer models require a whole entourage of specialists to create and maintain the software and hardware, to research global conditions required to initiate model runs, and to interpret the model forecasts.

Between the extremely simple subconscious models and the very complex GCM climate models there is a complete range of modeling activities in which humans are continually engaged. Our ability to construct complex conceptual models for forecasting future situations may have been an important element in achieving evolutionary success. We can only hope that this same capability can prevent us from destroying the global environment.

Reconstructing Past Situations

Models are used to reconstruct past situations based upon remnant evidence of the past and an understanding of present system behavior.

We also use our modeling skills when we look backward in time. In your favorite detective or mystery novel, the main character's mission is probably "to reconstruct the crime." This is a conceptual modeling activity similar, but not identical, to the problem of forecasting the future. Both past and future models are dependent upon understanding present system behavior (the laws of nature applied to the system). We will see, however, that these two kinds of models require different methods.

Models of the future start with the conditions or parameters of the present, which we assume we know well; modelers refer to these as the initial conditions. For example, in our model of milk consumption, the amount of milk in the refrigerator was an initial condition. It is obvious that we must start the model with the correct values or we will never correctly forecast future values. Starting with the proper initial conditions, a future forecast model allows time to proceed forward and describes the status of all the system variables as a function of this progression in time. Some models evolve to a steady-state solution, which is independent of the initial conditions given to the model. The initial conditions determine the path taken by the evolving model, but the final state of the model can be reached by many different paths.

Why can't we just run a future forecast model backwards in time to describe some previous situation? The simple and straightforward answer to this question is that nature doesn't work that way; we cannot force natural systems to run backwards.

When energy goes from one form to another, it always goes from a more concentrated, more useful form to a less concentrated, less useful one. For example, when a furnace burns oil or gas, the energy is dispersed into the atmosphere as heat. That energy is still present in the universe, but it cannot be recovered easily for human needs. Scientists use the concept of entropy to measure the disorder in a system. When concentrated energy is used to make dispersed energy, the system (which is the energy) is more disorganized; its entropy is greater. The second law of thermodynamics states that entropy always increases during natural processes.

It is the second law of thermodynamics that forces time to change in only one direction. Since entropy is one of the parameters that describe the state of a natural system, and since it can only increase, then the system itself can only change in such a manner that its entropy increases. Reversing time would require changes in the system that would decrease entropy; this is not allowed.

How, then, do we use a model to reconstruct the past? We must hypothesize a set of initial conditions for the system for a period of time that coincides with or just precedes the time that we want to model. The model is then run forward from that point in time to produce a set of system parameters for the time period being reconstructed. Why do you need the model if you know the initial conditions? Good question. The value gained in the modeling is that the model produces a complete set of consistent system descriptors, whereas the data from which the initial conditions were hypothesized were probably incomplete. For example, in modeling past Earth climates, geologists can tell us the location of the continents, the extent of the glaciers on the land, and the sea level for some particular time in the past. To this oceanographers can add the temperature of the sea surface, the volume of global ice, and the extent of sea ice. Climate modelers can use this information to hypothesize a set of initial conditions for a GCM; the GCM can then produce global data on air temperature, winds, precipitation, and other parameters that can be derived from the climate model variables. The model can tell us whether the glaciers were growing or shrinking, where specific plant and animal species could have been thriving, and the location of the major ocean currents.

How can the model start with a small quantity of input data and produce a complete global climate description? It has been programmed with the laws of nature and has been tested (trained) to properly simulate the present Earth climate system; therefore, altering some of the initial conditions usually does not present the model with any problems that it cannot handle. If, however, the model is presented with initial conditions that require science that has not been included in the model, then the output will be incorrect, albeit probably interesting.

The GCMs are so large and require so much computer time to run that the normal operation for forecasting the future (starting with today's initial conditions and running forward to the desired future time) is often very difficult and expensive. For these large models the methodology for forecasting the future is the same as for reconstructing the past. A set of future initial conditions is hypothesized and the model is run to achieve a steady-state or equilibrium climate that is consistent with the hypothesized initial conditions. (Upon reaching the steady state, the average values of the system variables remain constant.) Since there are no records with which we can compare the output, there is no way to independently check the model's results. This technique is best used to evaluate deviations from today's climate owing to specified changes in the input parameters, such as the effect of doubling CO_2 in the atmosphere.

Sensitivity Studies

Models are used to evaluate a system's response to a specified change in one of its parameters or variables.

A sensitivity study examines how a model responds to a series of changes in its initial conditions or parameters. Frequently, the interaction being investigated involves only one component of the whole system. In such cases the sensitivity studies can be performed on a smaller model prior to involving a large, expensive GCM run.

Sensitivity studies are vital in evaluating the importance of various feedback components in the natural system. A feedback is a process that responds to a system change by enhancing or diminishing the change. (For example, if the Earth cools, ice sheets are likely to grow; they will reflect more solar radiation, which causes further cooling. This process is a positive feedback.) The Earth system has many feedback processes, some of which we do not yet fully understand; sensitivity studies are useful in discovering which are more likely to produce global responses.

Another use for sensitivity studies is in investigating system behavior and interactions: how the system works. Unlike with forecast models, in which great care is taken to use the most accurate initial conditions and system parameters so that the model output will be believable, we can use sensitivity studies to push the system into unlikely situations that will expose the model to unanticipated responses and interactions. Sometimes this will expose errors in the model structure, and at other times it will provide new insight into the model dynamics. Sensitivity studies are tools for testing models, exploring model behavior, and learning how the system responds.

Understanding System Behavior

Modeling a system and running the model helps us understand how the system works.

In a rare case a newly created computer model will work on the first attempt. Experienced modelers and programmers can tell you many stories of "bugs" in their computer models that caused unexpected results and in some cases spectacular failures. These are almost never the computer's fault. Computers do exactly what they are told. Creating a good working model, even a simple one, forces the modeler to think clearly and succinctly about the system being modeled; computer models do not tolerate sloppy thinking.

Having created a working model, the next step is to test it. The testing is done by providing the model with input data for which there is a known result. One procedure for testing GCMs is to give them initial conditions that correspond to today's Earth (Earth-Sun relationships, location and size of continents and permanent ice, atmospheric gas concentrations, etc.) and allow the computer to run the GCM until the simulated climate system reaches a steady state solution. If the model forecasts ice sheets in Oklahoma, we should be suspicious. Other tests use extreme conditions. For example, if we turn the Sun off in the model, the Earth's temperature should evolve toward zero; if it doesn't, then we must go back to the drawing board.

When a model has been verified, we are ready to explore its performance and limits. This can be fun, like taking a new car out for a test drive. A range of system parameters and initial conditions is used to exercise all of the system interactions and to drive the system to certain defined limits. In addition to providing further testing of the model, this exploratory probing of its capabilities will reinforce our understanding of the system, and frequently the unexpected answers will give us new insights into system behavior.

Exercises

1. Treat the question "Can I afford to eat out tonight?" as we did the question "Do I need to buy more milk?" List all of the procedures and decisions that should go into responding to the question.

2. Consider a system composed of a marble and a wok and the system behavior when the marble is released at the edge of the wok. Describe the behavior of this system with different initial conditions, such as a simple release at the edge or a release with a sideways push on the marble. Does this system have a steady state solution? Discuss. Is the system behavior reversible with respect to time? Why?

F. Cellier, Continuous System Models, Springer Verlag, 1991

1.8 Good Reasons to Use Simulation

Let me state a number of good reasons for using simulation as a problem–solving tool.

(1) The physical system is not available. Often, simulations are used to determine whether a projected system should ever be built. So obviously, experimentation is out of the question. This is common practice for *engineering* systems (for example, an electrical circuit) with well–established and widely applicable meta–knowledge. It is very dangerous to rely on such a decision in the case of systems from soft sciences (the so–called *ill–defined systems*) since the meta–knowledge available for these types of systems is usually not validated for an extension into unknown territory.

(2) The experiment may be dangerous. Often, simulations are performed in order to find out whether the real experiment might "blow up," placing the experimenter and/or the equipment under danger of injury/damage or death/destruction (for example, an atomic reactor or an aircraft flown by an inexperienced person for training purposes).

(3) The cost of experimentation is too high. Often, simulations are used where real experiments are too expensive. The necessary measurement tools may not be available or are expensive to buy. It is possible that the system is used all the time and taking it "off–line" would involve unacceptable cost (for example, a power plant or a commercial airliner).

(4) The time constants (eigenvalues) of the system are not compatible with those of the experimenter. Often, simulations are performed because the real experiment executes so quickly that it can hardly be observed (for example, an explosion) or because the real experiment executes so slowly that the experimenter is long dead before the experiment is completed (for example, a transgression of two galaxies). Simulations allow us to speed up or slow down experiments at will.

(5) Control variables (disturbances), state variables, and/or system parameters may be inaccessible. Often, simulations are performed because they allow us to access *all* inputs and *all* state variables, whereas, in the real system, some inputs (disturbances) may not be accessible to manipulation (for example, the time of sunrise) and some state variables may not be accessible to measurement. Simulation allows us to manipulate the model outside the feasible range of the physical system. For example, we can decide to change the mass of a body at will from 50 kg to 400 kg and repeat the simulation at the stroke of a key. In the physical system, such a modification is either not feasible at all or it involves a costly and lengthy alteration to the system.

(6) Suppression of disturbances. Often, simulations are performed because they allow us to suppress disturbances that are unavoidable in the real system. This allows us to isolate particular effects, and may lead to a better insight (intuition) into the generic system behavior than would be possible through obscured measurements taken from the real process.

(7) Suppression of second–order effects. Often, simulations are performed because they allow us to suppress second–order effects (such as nonlinearities of system components). Again, this can help with the understanding of the primary underlying functionality of the system.

Page 15

When should we use what type of model? Walter Karplus generated a "rainbow" (the way children draw it) that answers this question in a systematic way [1.5]. Figure 1.5 represents a slightly modified version of that "rainbow."

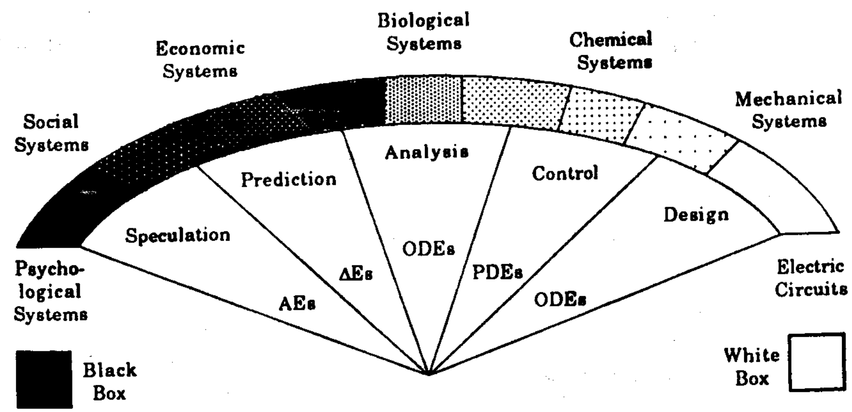


Figure 1.5. Spectrum of modeling and simulation.

Above the rainbow, various application areas of modeling and simulation are shown. They range from electrical circuits to psychological systems. The application areas shown are exemplary. Areas that are not shown include the thermal, hydraulic, and pneumatic system ich should be located somewhere between the mechanical and the chemical systems. In this text, we shall proceed along the rainbow from the right to the left, i.e., from well-defined ("white box") systems to ill-defined ("black box") systems.

Immediately below the rainbow, common purposes for modeling and simulation are specified. Remember that modeling and simulation are always goal-driven, i.e., we should know the purpose of our potential model before we sit down to create it.

Electrical circuits are so well understood that it is possible to use a model to design an overall circuit, i.e., once the performance of the model is satisfactory, we can build the real system, and, in all likelihood, it will work just as predicted by the model. This is also true for some of the mechanical systems (except where nonlinearities and friction effects become dominant factors).

This is, however, no longer true for chemical systems. Many factors influence a chemical reaction, factors which are all of approximately equal importance. Therefore, models that are valid for a large set of experiments cannot be specified. Thus, a theoretically derived model of a chemical process may predict one thing while the real system that is built after the model may react quite differently. Yet, if we build the system first and match the model to the system, the model contains sufficient internal validity to allow us to build a model of a controller for the system that, when applied to the real system, may still work nicely. This is due to the fact that feedback controllers have a tendency to reduce the system's sensitivity to parameter variations.

When we proceed further to the left, we find that the internal validity of our models decays further and further. Eventually, we come to a point where the available models no longer contain sufficient internal validity to allow us to use the model for any design purposes. Yet, we can still use the model for analyzing the system behavior, i.e., the internal structure of the model is still sufficiently valid to allow us to reason competently about cause-effect relationships among the variables that are captured by the model.

Advancing further to the left, we come to a point where even this statement is no longer true. Such models are constructed in a mostly inductive manner and a decent match between model and system behavior no longer guarantees that the internal structure of the model represents the internal structure of the real system in any meaningful way. Yet, we may still be able to predict the future of the real system from simulating the model beyond the current time.

Finally, systems exist where even this is no longer tru ll we can achieve is to speculate about possible futures, maybe with probability tags attached to the various possible outcomes. This is true in particular for social and psychological systems since they are retroactive. These systems include humans who, due to their knowledge of the model predictions, will adjust their behavior to modify that same outcome. In some cases, we end up with self-fulfilling prophecy. If I have a "good" model of the stock market that predicts the growth of a particular stock and if many people have access to that model and believe in its value, then all these people will wish to buy that particular stock, and sure enough, the stock will gain value (at least for a while). The opposite can also occur. If my model predicts a major disaster and if a sufficiently large number of influential people know about that prediction and believe in the accuracy of my model, they will do their best to modify the system behavior to prevent that very disaster from happening. Good examples are George Orwell's book *1984* and Jay Forrester's world model, which predicted clearly undesirable futures. Consequently, legislative actions were taken that hopefully will prevent those very predictions from ever becoming a reality. Walter Karplus wrote rightly that the major purpose of such models is to "arouse public opinion" [1.5].

Below the purpose spectrum, a methodology spectrum is presented. Electrical circuits can be accurately described by ordinary differential equations, since the influence of geometry is usually negligible. This is true except for very high frequencies (microwaves) or very small dimensions (integrated circuits).

When geometry becomes important, we must introduce the space dimensions as additional independent variables and we end up with distributed parameter models that are described by partial differential equations. This is true for mechanical systems with finite stiffness, for thermodynamics, fluid dynamics, optics, and diffusion processes in chemistry.

Advancing further to the left, the available data and the limited knowledge of the meta-laws of these systems no longer warrant the specification of distributed parameter models and we use again ODEs, not because that is how these systems really behave, but because we cannot validate any more complex models with our limited understanding of the processes and with the limited experimental data available.

When even less information is present, the accuracy that ODEs provide (and that we must pay for in terms of computing time) is no longer warranted. It makes sense to use very high-order integration algorithms only for the best-defined systems, such as those in celestial mechanics. When we simulate a celestial mechanics problem, we like to use an eighth-order Runge–Kutta algorithm, since it allows us to select a large integration step size and yet integrates the model equations with high accuracy. Fourth-order algorithms are optimal for most engineering tasks. As a rule of thumb, we use a k^{th}-order algorithm if we wish to obtain results with an accuracy of k decimals. For systems with an inherent accuracy of several percent (such as in biology), it does not make sense to use any integration algorithm higher than first order, i.e., the forward Euler algorithm shown in Eq.(1.6) is appropriate. Such models are therefore often represented in the form of *difference equations* (ΔEs).

Finally, in the "darkest" of all worlds, i.e., in social and psychological modeling, the models used are mostly static. They are described by *algebraic equations* (AEs). They are usually entirely inductive and depend on "gut feeling" or the position of the stars in the sky.

1.10 Direct Versus Inverse Problems

Envisage a system as depicted in Fig.1.6.

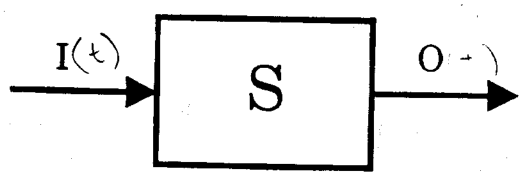


Figure 1.6. Block diagram of a system.

The system is characterized by a set of *inputs* (I) (including both control inputs and disturbances), by a set of *outputs* (O), and by a set of *internal variables* (S) including both the state variables and any auxiliary algebraic variables.

The "normal" situation for a simulation is given, when all inputs are known as functions over time, and when the system structure and the initial conditions of all state variables are specified. The task of the simulation is to determine the trajectory behavior of all outputs, i.e.,

$$\mathbf{I}, \mathbf{S} = \text{known} \; ; \; \mathbf{O} = \text{unknown}$$

This problem is called the *direct problem.*

However, two types of inverse problems exist as well. For instance, it could be that the system under study is a "black box." While all inputs and outputs are known, the internal structure of the system and/or the initial values of the state variables are unknown, i.e.,

$$\mathbf{I}, \mathbf{O} = \text{known} \; ; \; \mathbf{S} = \text{unknown}$$

These problems are referred to as the *structure identification problem* and the *state estimation problem*, respectively. We shall demonstrate in the companion book how simulation can be used to solve identification problems.

A third type of problem is given if:

$$\mathbf{S}, \mathbf{O} = \text{known} \; ; \; \mathbf{I} = \text{unknown}$$

This is referred to as the *control problem* and is the major subject of the area of automatic control [1.3,1.4]. In the companion book, we shall also demonstrate how simulation can be used to solve control problems.

1.11 Summary

In this chapter, we have given some basic definitions, outlined the scope of our undertaking, and tried to answer the question why students might be interested in this subject and why they might want to continue with this course.

References

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[1.2] Brian Gaines (1979), "General Systems Research: Quo Vadis," *General Systems Yearbook*, **24**, pp. 1–9.