Chapter 1

The Biosystems Engineering

TOPICS

- The **Bio**sphere
- **Systems** concepts
- **Engineering** principles

The field of Biosystems Engineering is emerging in response to such major concerns as environmental integrity, food safety and quality, water security, and natural resource availability. **Biosystems engineering is defined here as the analysis, design, and control of biologically-based systems for the sustainable production and processing of food and biological materials and the efficient utilization of natural and renewable resources in order to enhance human health in harmony with the environment.** In this course, biosystems engineering is introduced to address the large, complex, and time-dependent nature of biophysical systems. However, the principles and examples can be applied and extrapolated to lower-level structures, such as cells, organelles, organs, and organisms.

There is a growing worldwide concern for saving the environment from human abuses and harmful actions. Such activities include irresponsible exploitation of our natural resources, deforestation, pollution of air and water, dumping of non-biodegradable products in our soil, uncontrolled production of ozone-depleting chemicals, acid-rain effects in forests and lakes, and the overall degradation of the environment. Human abuses have slowly destroyed our life support systems. Consequently, the supply of safe food and water is increasingly compromised. The major culprit, among other things, is the lack of understanding of the dire consequences of uncontrolled economic development, unregulated technological advancement, and mismanagement of natural resources.

Coupled with environmental dilemma is the fact that human population is growing exponentially. While human population is expanding, natural resources are declining. According to the World Population Prospects of the United Nations (Archer, et al., 1987) human population will reach close to 8 billion in the year 2020. This implies that there will be more people competing for the consumption of the same amount of natural resources, as illustrated in Fig. 1.1. Air, water, and soil pollution, resource depletion, social chaos, and political upheaval are some of the consequences already demonstrated and are expected to get worse in the future.

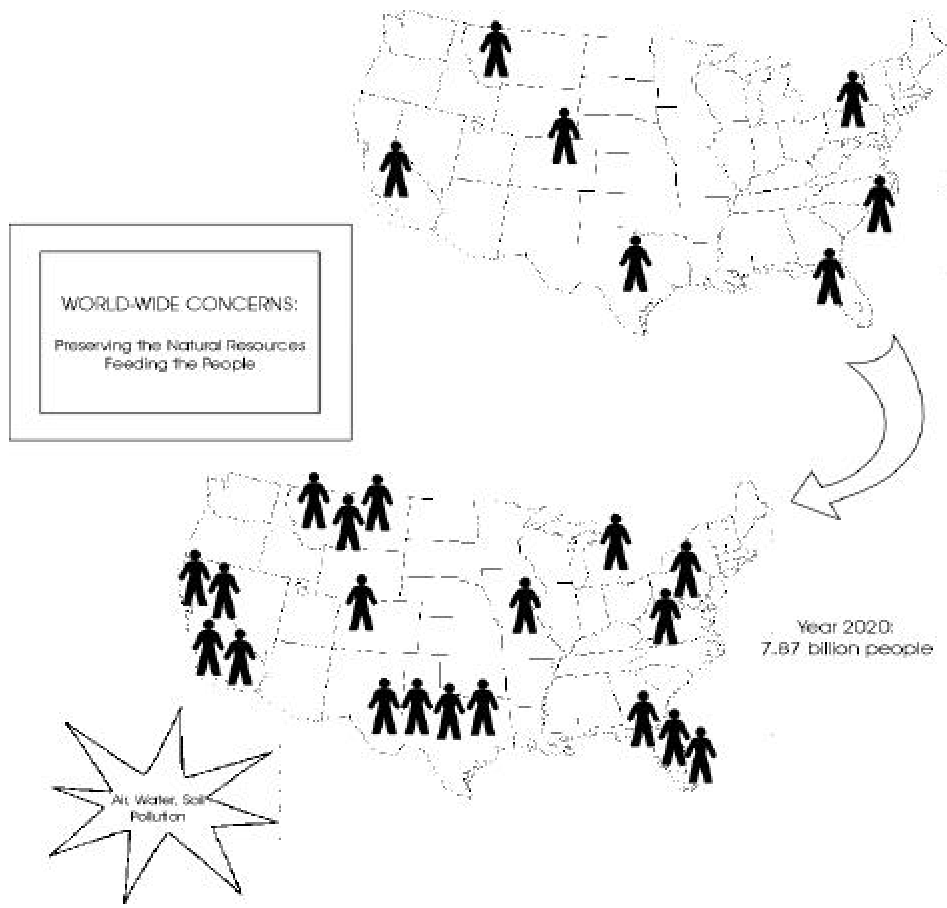


Figure 1.1. Schematic representation of population growth without resource growth, resulting in environmental consequences.

Human-initiated activities have already altered many environmental situations worldwide. For example, cutting down of trees has increased soil erosion; industrial operations have polluted the atmosphere; voluminous human and industrial wastes have resulted in soil and water pollution; the quality of air and water in many cities has reached hazardous level; and changes in heat and water balances in the atmosphere and hydrosphere due to air and water pollution may be factors affecting adverse climatic patterns. Not seen before are the emergence of disease-causing and antibiotic resistant bacteria, such as *Escherichia coli* O157:H7 and *Salmonella typhimurium* DT 104. If the changes in the physical and chemical environments are more extreme than the variations to which human and other living organisms in the ecosystem can adapt, the ecological harmony may be irreversibly disturbed. Therefore, all possible steps should be taken to put an end to the deterioration of the natural environment, as our expression of concern for the future generation. A step toward this end is to analyze problem with global implications in a holistic manner and to propose solutions that reflect the consideration of the whole biosystem. It is the responsibility of the present generation to maintain a balance among food supply, economic development, and environmental protection in order to provide for, and ensure the survival of, the future generations.

1.1 The Biosphere

While the concept on the environment involves a complex system of interacting living and non-living components encompassing the whole universe, for practical and obvious reasons, let us begin with the biosphere as a component of planet Earth. The biosphere is the space where biotic and abiotic worlds meet, at the overlap and interface of the three major spheres: atmosphere, lithosphere, and the hydrosphere (Archer et al., 1987), as illustrated in Fig. 1.2. It is the common ground shared by humans and other living organisms, constantly interacting with one another (Fig. 1.3). These living organisms also exchange matter and energy with their environment. It is in this sphere where the most pressing problems of the environment exist. In general, we shall refer to a system structure in the biosphere involving a biological component as a biosystem. In particular, the biosystem is defined here as any form of organization which is made up of living and non-living components, interacting and interconnected as to achieve a unified purpose, specifically with respect to food production, environmental preservation, economic development, and technological advancement.

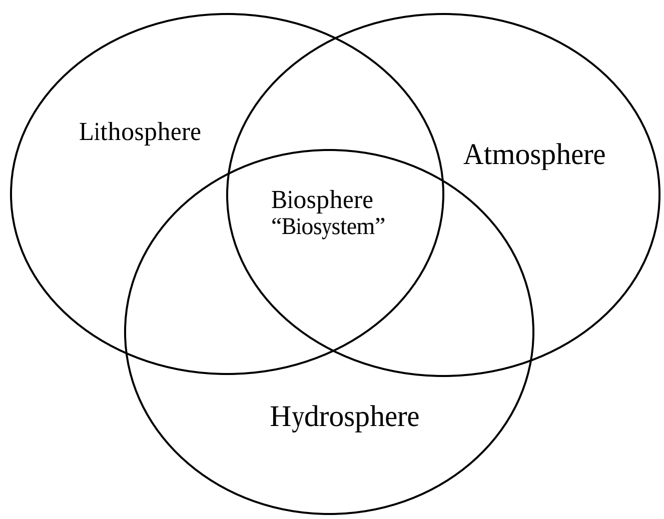


Figure 1.2. Schematic representation of the biosphere as an interface of the atmosphere, lithosphere, and hydrosphere.

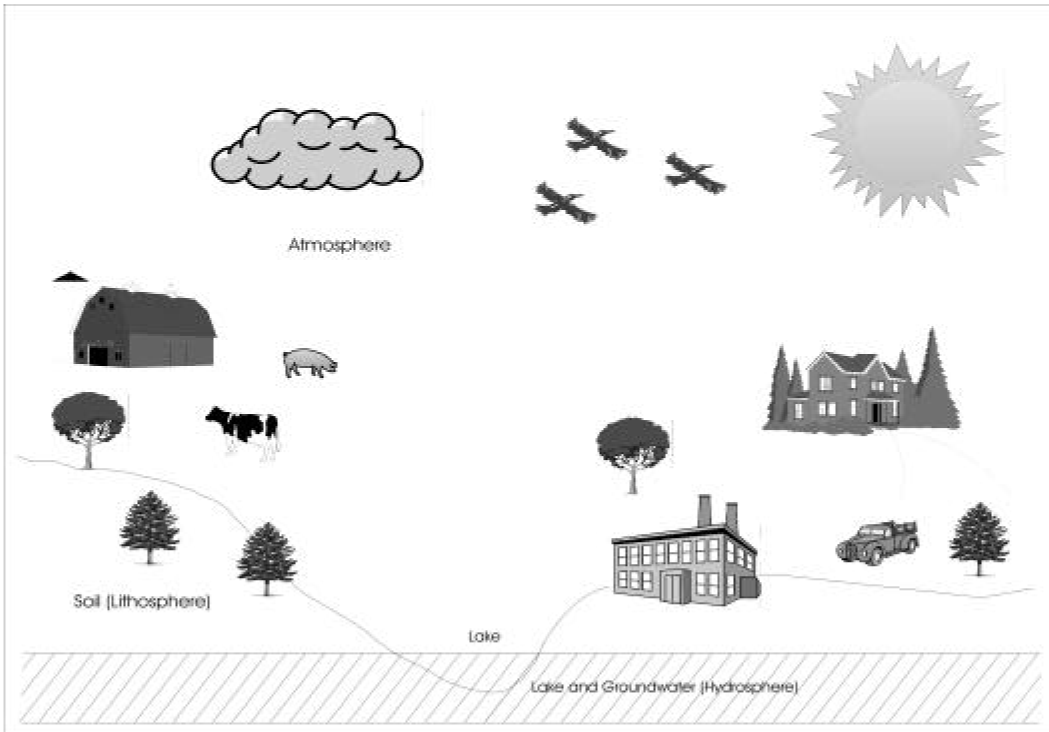


Figure 1.3. Schematic of the biosystem in the biosphere.

1.2 Systems Concepts

System. The word "system" can be defined as anything formed of parts or components placed together and interconnected to make a regular whole working as if one body or entity as it relates an input to an output, or a cause to an effect. There are at least four concepts in this definition. First, a system is made up of **components** or **subsystems** which have defined relationships. Second, each of these components are **linked** in such a manner that the output of one is an input to the other. Third, the successful operation of one component depends upon the other (**unity**). And fourth, system components are interconnected to form one body or entity in order to achieve its **purpose**. A plant is a good example of a biological system. Plant growth is orchestrated in its internal mechanism as to reproduce itself. Under favorable conditions, a corn plant will bear corn grains (not rice nor wheat grains). The photosynthetic process of converting solar radiation into carbohydrates and finally biomass is a series of interconnected transformations. When photosynthesis fails, biomass will not be produced. A car, an airplane, a computer, a microscope, a dog, a tree, a house, a population, a person, a bacteria, and a cell are each an example of a system.

Associated with the word "system" are terms that need clear understanding and comprehension. These words are input, output, parameters, state variables, boundary, and environment. There are two kinds of input: controllable and exogenous. Similarly, there are two kinds of output: desired and undesired. There definitions are presented as follows.

Controllable Input. The controllable input variables are materials or energy which are required to bring about the desired system output. These variables can vary with time. For example, water is a material input in soil-plant systems, animal production systems, and river or lake systems. The volume of water flowing into a river may vary during the day. Food intake is a controllable input to the body.

Exogenous Input. The exogenous input variables are materials or energy, which influence or affect the biosystem but the biosystem cannot affect them (at least for the system under consideration). For example, solar radiation, air temperatures, and rainfall are exogenous input to people, forest, crop, urban, and economic systems.

Desired Output. The desired output variables are the transformation product of the material input and the system processes (accounting for technologies) through the use of energy and labor. For example, forage and grain are desired outputs of the corn production system; milk, meat, eggs, and fur are desired outputs of the animal system; profit is a desired output of a farm system; potable water is a desired output of a regional system.

Undesired By-Products. The undesired by-products are the undesirable results as the biosystem functions to produce the desired outputs. For example, nitrate leaching is an undesired by-product of crop production system; phosphate runoff is an undesired by-product of animal production system; water pollution is an undesired by-product of an industrialized economy.

State Variables. The state variables summarize the status of the system. Knowing the state variable (S) at any initial time t_0 and the input function (I) at time t_0, together with the equations describing the dynamics of the system, it should be possible to know the state of the system at any time t_1 where $t_1 > t_0$. That is,

$$I(t_0) + S_0(t_0) \rightarrow S_1(t_1)$$

State variables can be classified into two: feasible and infeasible. The feasible states are variables that satisfy the constraints of the system and therefore are valid information in assessing the status of the system. The infeasible states are variables that violate at least one constraint. For example, the weight of leaves, stems, grain, and roots are state variables of a plant system; the amount of biomass and milk are state variables of a dairy system.

System Parameters. System parameters are factors, which determine the initial structure and condition of a biosystem. In mathematical equations, these are constants representing technology or information. Parameters are differentiated from state variables in that, for deterministic systems, they do not change with time during the operation of the system.

System Boundary. System boundary is the separation (real or imaginary) between the system and the environment. For example, the physical boundary of a household system may be the house structure itself, that is, everything inside the house belongs to the system; everything outside belongs to the environment.

Environment. For any given biosystem, there is an environment. This environment is the set of all objects, factors, and influences outside the boundary of the system. All signals from the environment crossing the boundary into the system must be one-way direction, that is, the signal may affect the system but the system output should not affect the environment to the extent that it would modify the signal (Eisen, 1988). The environment may occur in the following forms:

1. Natural environment -- For a biological (e.g. crop production) system, the natural environment may include solar radiation, rainfall, ambient temperatures, and wind speed.

2. State-of-resource-and-technology environment -- Formulation and structuring of a crop production system may be affected by the type of irrigation to be employed, or the crop variety to use, or the fertilizer management to practice. It is also affected by the availability of production inputs, accessibility to markets, etc.

3. State-of-knowledge environment -- Knowledge of the processes affect the formulation and synthesis of a biosystem. When there is no clear understanding of the biosystem, a less efficient and less sustainable management approach is likely to be used. For example, our lack of deeper understanding on the extent and ill-effects of nitrates and pesticide residues in groundwater contributed to the neglect of sustainable practices in manufacturing industries, farms, golf courses, household gardens and lawns, and other operations.

4. Institutional and Social Environment -- The institutional, organizational, and social structures, such as government laws, regulatory bodies, lobby groups, commodity associations, social customs, personal preferences, and manpower skills, may influence the evaluation of objectives and the structuring of the biosystem. For example, certain commodities dominate the market because of trade agreements.

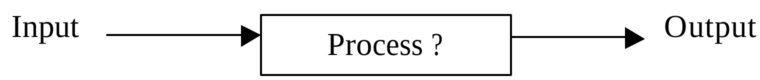
5. Economic Environment -- Input costs, product prices, marketing costs, and other economic factors affect the formulation, structuring and synthesis of a biosystem. For example, cheaper inputs are likely preferred over more expensive materials.

1.3 Engineering Principles

Basic engineering skills include analysis, design, and control.

Analysis. Analysis is the process of finding the solution (output) of a specified system process, given a description of the system inputs. For example, a nutritious food (input) fed into a healthy body (system process) could result in muscle gain (output). An analysis can be done to determine the amount of muscle gain for every gram of food intake in the same body structure. In the analysis, the amount of food intake may be varied and the gain observed. Schematically, analysis can be represented as follows:

Design. Design is the specification of the system process in order to match specific input to desired output. Continuing on our body example, two people given the same amount of food may gain weight differently due to differences in their body structure. To compensate for the difference, one person may be advised to get more exercise in order to achieve the same weight gain. The concept of design can be diagrammed as follows:



Control. Control is the specification of inputs in order to achieve desired outputs given a description of the system process. An individual may be prescribed a set of food to achieve a desired weight gain. In schematic presentation, the relationship can be seen as follows:

Systems analysis is the application of organized analytical modeling techniques appropriate for explaining complex, multivariable systems (Vaidhyanathan, 1993). Our efforts in this course shall be directed towards the application of modeling techniques to understand important dynamic phenomena for the continuing stability of the biological system. The study shall be guided by the principles of growth, conservation of mass, cybernetics, stability, and sustainability.

Growth is the principle of gradual development of living matters toward maturity. It is a process involving an increase in size, weight, power, wisdom, and many other factors. Decay is the antithesis of growth. A gradual decline in strength, soundness, health, beauty, and prosperity is part of decay. It is also a process involving decomposition and rotting. Chapter 4 will cover extensively the principle of growth.

Conservation of mass (as well as energy and momentum) is the principle that matter cannot be created nor destroyed during a physical or chemical change. Within a closed system, the rate at which a substance increases or decreases is due to the rate at which the substance enters from the outside minus the rate at which it leaves. However, while matter cannot be destroyed nor created, it can be transformed, transported, and stored. Conservation equations are "bookkeeping" statements: they serve to keep track of all substances within the boundary of the system, including the initial conditions. More discussions and illustrations will be presented in Chapter 5.

Cybernetics is the science of how systems are regulated. The cybernetic structure can either be open-loop or closed-loop. An open-loop biosystem can be partitioned into two major structures: the *bio-control* and bio-*process* structures, as illustrated in Fig. 1.4. The *bio-control* structure receives the external input signal which represents a goal, an objective, or a reference of what is desired to be achieved. The *bio-process* structure takes material resources and/or energy and acts on them to produce the outputs. This structure is subject to disturbances, which may cause variations in the output and in the process itself. In an open-loop biosystem, the actuating signal can be altered at any time based on the objective of the output and all other prior knowledge about the process. This actuating signal is not influenced by the output of the system at any time.

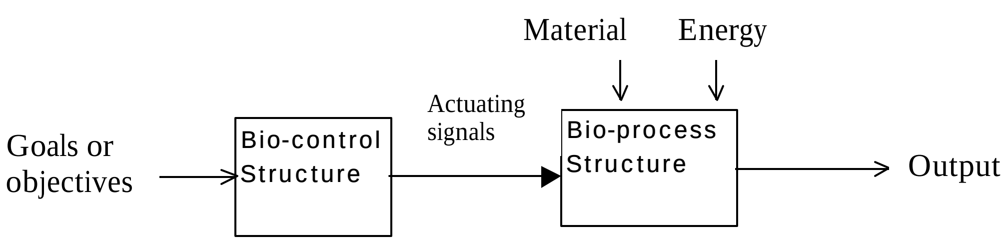


Figure 1.4. A generalized structure of an open-loop biosystem.

However, when the output affects the input signal, then the system is called a closed-loop biosystem as shown in Fig. 1.5. In this case, a *bio-sensor* or control measurement is present, which consists of a measuring device to record output signals and convert them into internal input signals to the *bio-control* structure. The internal input signals provide the *bio-control* structure with information on what is happening in the *bio-process* structure. The engineering of the biosystem consists of defining the nature of the *bio-control* structure, the character of the *bio-process* structure, and the description of the *bio-sensor* so that the outputs agree with the objective for which the biosystem is being directed.

The biosystem structure in Fig. 1.6 can be broadly represented by a *control* structure that is human-dominated interfacing with the *real* structure (natural, biological, and physical) as shown in Fig. 1.6 (Alocilja and Ritchie, 1992). The decision maker resides in the *control* structure. It is in this structure that objectives are defined and subsequently, decisions on controllable inputs are made in order to achieve the desired outputs, manage the undesired by-products, and control the transformation processes. The decision maker in the *control* structure determines how the processing components in the *real* structure are interconnected. The *real* structure, on the other hand, is the object of control. It is composed of the natural, biological, and human-made physical systems. This structure is multi-level and requires an integration of multidisciplinary sciences. Constraints in the *real* structure are fed back to the *control* structure. The *control* and *real* structures are, therefore, highly coupled: the objectives as defined by the *control* structure, determine the interconnections of the processes in the *real* structure, while the statement of objectives in the *control* are constrained by the boundary conditions existing naturally, biologically, and technologically in the *real* structure. Examples 1.1 and 1.2 provide illustrations of open-loop and closed-loop systems. Chapter 4 will illustrate further the concept.

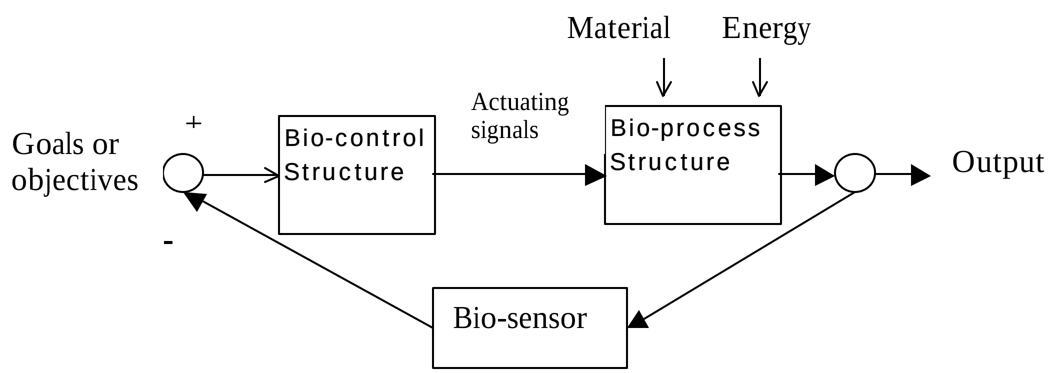


Figure 1.5. A generalized structure of a closed-loop biosystem.

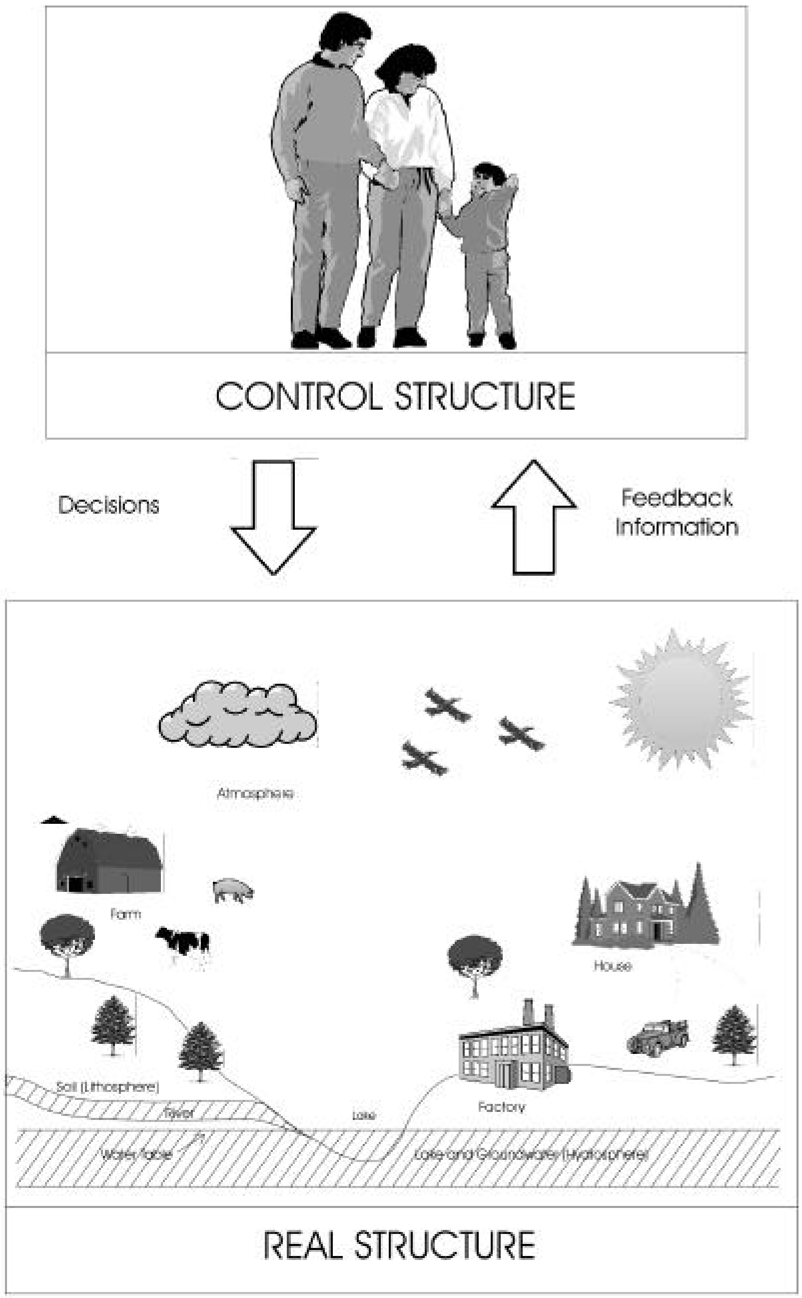


Figure 1.6. Schematic diagram of a human-controlled structure.

The important factor in a controlled system is the presence of feedback, which permits the system to compare what the effector is doing with what it is supposed to be doing. A feedback loop exists if variable x determines the value of variable y and variable y in turn determines the value of variable x. In living systems, examples of effectors are muscle cells, cells which secrete various chemicals into the bloodstream, or cells which transport substances from part of the body to another (Jones, 1973).

An example of an open-loop feedback system would be growing a corn plant to which water and fertilizer are regularly added without regard to the condition of the plant. Wilted or flooded, water is added regardless. The adding of water and fertilizer is not influenced by how much the plant needs at any given time. In this case, the flow of information is in one direction; there is no return flow or "feedback" of information as to the actual situation of the plant. Figure 1.7 illustrates the concept graphically.

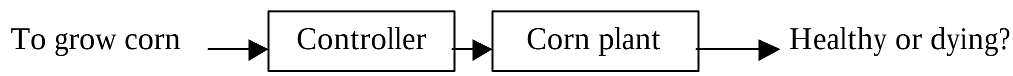


Figure 1.7. Schematic diagram of an open-loop corn plant culture.

Suppose the controller varies the amount of water according to how the plant looks at any point in time. If the plant looks wilted, water is added; if the plant looks "sick", fertilizer is added; if the soil feels saturated, water is suspended. In this instance, there is an information flow from the plant, which the controller uses to regulate the input of water and nutrients. In this case, the system is closed-loop feedback and illustrated in Fig. 1.8.

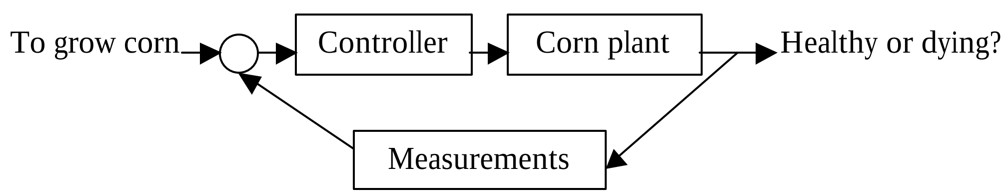


Figure 1.8. Schematic diagram of a closed-loop corn plant culture.

Ecosystems act as open loop systems because they receive radiant energy from the sun and moisture from rain and snow which they cannot influence by feedback. Living things in the ecosystem are influenced by temperature, which the system has no control over. However, ecosystems also act as closed-loop systems because there are many ways whereby they can regulate the flow of materials or the effect of various physical impacts on them.

Negative feedback regulation is often referred to as deviation-counteracting feedback, or homeostasis (DeAngelis et al., 1986). Many ecological systems have generally been thought of as homeostatic systems. Although there is still disagreement on the precise interactions responsible for the negative feedback and on how tightly it regulates various ecological systems, there is some concensus that negative feedback regulation is occurring at least to the degree that it normally keeps populations and communities from going completely out of control, although it may not always be strong enough to prevent sizable fluctuations. Positive feedback occurs when the response of a system to an initial deviation of the system acts to reinforce the change in the direction of the deviation.

When a population or ecological community is perturbed slightly from equilibrium, the balance of negative and positive feedback mechanisms in the system tends to counteract the perturbation and restore the system to equilibrium (if this equilibrium is inherently stable). Neither positive nor negative feedbacks manifest themselves individually in a conspicuous way. However, when the population or community is driven far from equilibrium (by a temporary unusual environmental condition, for example), specific positive or negative feedback may become very obvious. The system could be driven into a regime homeostatic forces no longer operate. Positive feedback loop may act to amplify the deviation, perhaps deriving the system to extinction. On the other hand, other positive feedback loops may be activated that rescue the population from extinction and allow it to increase to the point where homeostatic forces restore it to equilibrium. Pest or epidemic outbreaks and the survival of rare species in environments of scattered habitat islands are all problems that involve positive feedback in important ways.

The existence of a flow of information from the system "output" (in the example, the plant's appearance) to the controller that regulates the input to maintain a stable set point (a healthy plant), is a commonly accepted emblem of a cybernetic system. The systems considered in this chapter are more general than this in two ways. First, the feedback will not always be purely information flow, but may be a change in biomass, energy, or material that only incidentally conveys information affecting the system input. Secondly, the feedback in question will not necessarily maintain the system at a stable point, but may cause the system to change from one state to another.

Example 1.1. A rider-bike system

Consider a system structure of a person riding a bicycle. The rider-bike system can be decomposed into several components in a simplified manner, as shown in Fig. 1.9. The objective of the rider is to keep the bike in the center of the bike lane. The output is the actual path of the bike. An error in the difference between the objective and output are detected visually. This error detection activates the brain. The brain transmits signals to the rider's arms and muscles which control the steering handles and the wheel directions.

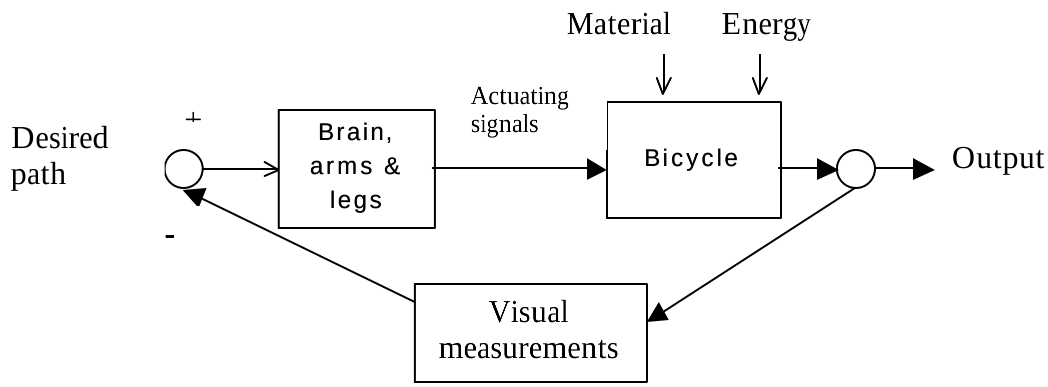


Figure 1.9. A schematic diagram of a rider-bike control system.

Example 1.2. A Plant-water system

Consider a system of a potted rose that is watered daily. The objective is to grow a beautiful, flowering rose bush. If water is added without regard to the condition of the plant, the system is an open-loop system. However, if water is added only when the plant needs it, or if the amount varies to meet the moisture requirement of the plant, then the system is a closed-loop system—the output (condition of the plant) affects the input (frequency and amount of water applied to the pot).

Related to cybernetics is the idea of homeostasis or stability of system behavior. Stability is concerned with how the system handles perturbations or disturbances. The basic notion of system stability is this: if a system initially at rest is disturbed, does it gradually return back to rest or does it wander away? If the system returns back to its rest position, then the system is stable; if it wanders away, then the system is unstable.

Sustainability is the philosophical paradigm that addresses economic growth and development within the limits set by ecology in the broadest sense—by the interrelationships of human beings and their works, the biosphere, and the physical and chemical laws that govern it (Ruckelshaus, 1989). The World Commission on Environment and Development (Haimes, 1992) defined sustainable development as the "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs." According to Haimes (1992), sustainable development has become the quintessential paradigm for addressing the worldwide dilemma of advancing our economic development while protecting environmental quality not only for this generation but future ones as well.

This book shall bring together many disciplinary sciences and study the interrelationships among them so that we may be able to learn, understand, and recognize the interconnections among food security, technological advancement, environmental integrity, and economic development. In so doing, biosystems engineers hope to be able to design and engineer a sustainable biosystem that will be compatible with, and able to accommodate, **change, complexity**, and **growth.**

🕮 Exercises

1. *Impacts of High Population.* Study the schematic diagram of Fig. 1.1. Identify the implications and effects of over-population. Note that people need three basic things: food, clothing, and shelter.

2. *Learning systems concepts from the headhunters.* In a remote forest, there happened to be three headhunters and three strangers arriving in the same place at the same time. Considering that there was a one-to-one ratio among them, peace prevailed. All were seeking to cross a river in a boat that can hold at most two people and can be navigated by one or two individuals. Due to their headhunting practice, the headhunters could not be allowed to outnumber the strangers at any time and at any place. All were able to cross the river in five and one-half round trips without mortality. How did they do it? Let the bank where the people were originally be designated as bank 1; the bank across be designated as bank 2. Identify the system boundary, system parameters, input, output, and state variables. Identify the feasible and infeasible states.

3. *Analysis and design of the International Center Food Court.* The International Center Food Court (ICFC) is the place to be during mealtimes. Conduct an analysis and suggest design improvement, if necessary, so customers are satisfied.

4. *Systems definition in lake pollution.* Pollution occurs when high amounts of nutrients, through soil erosion and waste disposal, end up in the lake. Nutrient accumulation favors the growth of certain tiny marine organisms called phytoplankton. These plankton blooms appear as patches on the surface of the water. During this process, oxygen in the water is depleted and other living organisms are affected. In such a condition, identify the system boundary, the environment, system parameters, input, output, and state variables of a lake system.

5. *Understand systems concepts in the classroom.* Consider BE 230 class as the system. For a given lecture hour, identify the controllable and exogenous inputs, state variables, desired output, undesired by-product, design parameters, and the different kinds of environment. Classify input and output as either material or energy.

6. *Fish tank.* Given a fish tank (12 ft long, 6 ft wide, 6 ft tall) with 5 fish in it (walls are the boundary), identify the following in **quantitative** terms: Controllable input (how much food is needed of each per day?), desired output, undesired by-product, state variables, system parameters, and environment. Illustrate (draw) your system.

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