The title of this paper, "Organizing the Rules of nature", brings forth the question: What are the rules of nature? Since nature, exclusive of man, does not state any rules, the rules must be something that man creates by his study of nature. You will probably agree that the rules of nature as we know them are the principles of the sciences. But what are the principles of a science? What do scientists mean by "principle"?

In 1947 I began asking biologists: What are the principles of biology? What do you mean by principle? I got no complete or consistent answers. I began noting how the word "principle" was being used and I listed every statement that some biologist called a principle. Most of these statements were generalizations by simple enumeration, but in my list were other kinds of statements. After years of questioning and reading and after years of studying the history and philosophy of science, I arrived at a simple definition of "principle". With few exceptions, the principles of biology are the major postulates of biological theories.

But what are theories? If you go to biology textbooks, you will find loose and unclear definitions. Gibbs and Lawson (1), who reviewed 13 college and 8 high school textbooks, found the term "theory" is a state of confusion. To one author a theory is a general statement, to another a theory is a conceptual scheme, to another a theory is knowledge correct and complete, and to another a theory is a hypothesis repeatedly verified. The verified hypothesis view is quite common. But what is a "hypothesis"? Is a hypothesis a guess about an unknown fact, or an untested deduction, or a set of assumptions, or a theory in the making, or the postulate of a theory, or a tentative explanation? Unfortunately it is all of these as the word is now being used. Therefore to define theory in terms of "hypothesis" is no help. It simply compounds the confusion.

According to A Dictionary of Ecology, Evolution and Systematics (2) a theory is "a scientifically accepted general principle supported by a substantial body of evidence offered to provide an explanation of observed facts and as a basis for future discussion or investigation." This definition is as misleading as those found in introductory textbooks. Is "All organisms are composed of cells" the cell theory? Certainly not. But it is a general principle strongly supported by evidence. "Inherited traits are determined by genes." This is another principle that is not a theory. So what is a theory?

A theory is a nearly geometric pattern of reasoning. Central to each theory are a few ideas stated in the postulates (basic premises, fundamental assumptions). Lines of reasoning build pattern in three ways. 1) They use facts to support a postulate. 2) They use facts and postulates to explain known facts. 3) And they use facts and postulates to predict possible new facts. Theories with this structure are found everywhere in the natural and social sciences and in a few places in the arts and humanities. A theory is an intellectual construct consisting of a few basic premises plus many facts and lines of reasoning. A theory is a hypothetico-deductive system of thinking. The postulates are the hypothetico part of the system. Explanation and prediction are the deductive parts of the system.

Figure 1 is a diagram of a theory. The P’s at the top are the postulates, the basic premises, of the theory. Usually there are from 5 to 9 postulates. The arrows represent lines of reasoning. The F’s represent facts and Pr, predictions. R1 is a line of reasoning that uses facts to support one or another of the postulates. R2 is reasoning that uses the postulates and facts to explain a possible new fact and R3 is reasoning that uses postulates and facts to predict a possible new fact. This diagram is misleading because it looks as though the bulk of the theory is the basic premises, the postulates, whereas they are usually the smallest part of a theory. The great bulk of a theory consists of dozens, hundreds, or thousands of facts and lines of reasoning.

Fig. 1. Diagram of a theory. The P’s are postulates, the basic premises. The R’s are lines of reasoning. R1 uses facts to support a postulate. R2 uses postulates and facts to explain a known fact. R3 uses postulates and facts to predict a possible new fact.

My description of theory is based on the study of more than 700 theories whose postulates I have listed. About 150 of these lists are from recent papers and about 100 have been corrected by their authors. Seldom do authors actually list their postulates. They usually scatter them along in their papers as Darwin did in describing his theory of descent with modification and his theory of natural selection in the Origin of Species.
My diagram of theory is consistent with Einstein’s as given in Holton’s paper (3), "Constructing a Theory: Einstein’s View". And I think my view of theory agrees with the philosophers views, but I am not too sure because philosophers love complexity and they fail to give dozens of examples.

Consider the germ theory of disease as an example of a theory. These are its postulates.
1. An infectious disease is caused by a microorganism, a parasite, growing in the host organism.
2. Each disease is caused by its specific kind of a parasite.
3. The host’s symptoms of a disease are due to the growth and other activities of the parasite living in the host.
4. A disease is transmitted from a host to a potential host by the active or passive transmission of the parasite.

Most biologists know many facts that could be used to support each postulate of this theory and many facts that could be explained by using the postulates. And given a particular situation, they could easily make predictions about what to look for. In recent years this theory came into play in discovering the cause of legionnaires disease and in the study of the cause of AIDS. In AIDS however, we may be in a situation that is beyond the range of the germ theory that has the above postulates. Sometimes the virus is present, but there are no symptoms. Sometimes the symptoms are present, but no virus is found. The AIDS situation may be due to the absence of some critical facts or it may lie outside the range of applicability of the germ theory of disease as we commonly think of it.

This latter possibility illustrates a characteristic of all theories. All scientific theories have limits to their range of applicability. Even well developed and well established theories, what I call "embedded theories", give us only a portion of scientific truth. All have boundaries beyond which they do not work. In examining any theory, one needs to get answers to these three questions.
1. What are the basic premises, the postulates, of the theory?
2. What are some examples of lines of reasoning used for support, for explanation, and for prediction?
3. What are the range of applicability and the limitations, the boundaries, of the theory?

It is essential that the postulates, the fundamental assumptions, of a theory be explicitly stated and identified. Morris Cohen in his Reason and Nature (4) emphasized this with these words: "It is essential to a scientifically logical system to seek to make its hypotheses or initial assumptions explicit." "This effort to make explicit those assumptions...characterizes science from the beginning...and promotes the attainment of truth." "By making assumptions explicit we are able to question them and to enrich our vision by thus revealing other possibilities." And through the decades other authors have repeatedly urged scientists to explicitly state the fundamental assumptions, the postulates, of their theories. Yet today I read dozens of papers in which this is not done.

Suppes (5) gave twelve reasons for stating postulates explicitly.
1. Great scientists have done it.
2. Clarifies concepts and make them explicit.
3. Makes explicit the fundamental assumptions.
4. Clarifies the total structure of a discipline.
5. Clarifies the relations of the parts.
6. Makes possible the recognition of common aspects of the intellectual enterprise.
7. Gives the kind of order that permits one to see both the forest and the trees.
8. Enhances objectivity by increasing clarity and reducing foggy meanings.
10. Simplifies by reducing the number of fundamental assumptions.
11. Provides the best way to convince an opponent of your theory.
12. Admits of efficient critical examination by others.

In the Origin of Species Darwin did not list the postulates of his two major theories, the theory of descent with modification and theory of natural selection. As with most papers today, the postulates are scattered throughout his discussions. Here are my lists of the postulates of these two theories as published in Evolution: A System of Theories (6). The numbers after each postulate are the pages in the first edition of the Origin on which the import of the postulate is found. Darwin did not use "evolution" in his statements, but I used "evolution" to make it easier for students to use the postulates.

Theory of Descent with Modification
1. All life evolved from one simple kind of organism or from a few simple kinds. 484, 490
2. Each species, fossil or living, arose from another species that preceded it in time. 6, 306, 316, 321, 341, 351, 356, 385, 389, 405, 461, 481, 486
3. Evolutionary changes were gradual and of long duration. 84, 102, 287, 302, 314, 343, 429, 459, 462, 463, 471, 475, 479
4. Over long periods of time new genera, new families, new orders, new classes, and new phyla arose by a continuation of the kind of evolution that produced new species. 125, 126, 128, 316, 351, 427, 462, 471, 474, 483
5. Each species originated in a single geographic location. 352, 356, 407, 427, 461, 487
6. The greater the similarity between two groups of organisms, the closer is their relationship and the closer in geologic time is their common ancestral group. 321, 412, 41, 420, 425, 426, 474, 477, 479, 485
7. Extinction of old forms (species, etc.) is a consequence of the production of new forms or of environmental change. 126, 344, 463, 471, 475
8. Once a species or other group has become extinct it never reappears. 127, 313, 316, 343, 344, 475
9. Evolution continues today in generally the same manner as during preceding geologic eras. 409, 480
10. The geologic record is very incomplete. 342, 345, 464, 475, 487

**Theory of Natural Selection**

1. A population of organisms has the tendency and the potential to increase at a geometric rate. 63, 64, 78, 109, 186, 322, 467, 470
2. In the short run, the number of individuals in a population remains fairly constant. 65, 67, 69
3. The conditions of life are limited. 63, 64, 67, 68, 140, 319, 322
4. The environments of most organisms have been in constant change throughout geologic time. 81, 107, 108, 126, 201, 314, 356, 382, 462, 468, 476
5. Only a fraction of the offspring in a population will live to produce offspring. 61, 63, 65, 66
6. Individuals in a population are not all the same: some have heritable variations (=variable traits). 60, 61, 102, 108, 127, 130-170, 459, 466, 474, 479, 481
7. Life activities (="struggle for existence") determine which traits are favorable or unfavorable by determining the success of the individuals who possess the traits. 53, 61, 62, 63, 79, 102, 109, 127, 459, 467
8. Individuals having favorable traits (=favorable variations) will, on the average, produce more offspring and those with unfavorable traits will produce fewer offspring. 61, 81, 82, 83, 84, 320, 344, 459, 476
9. Natural selection causes the accumulation of new variations and the loss of unfavorable variations to the extent that a new species may arise. 53, 470, 490

If one considers the postulates of these two theories as one reads a college general biology textbook, one will find evidence to support most of the postulates and one will find some explanations of known facts. And of course the Origin of Species is full of these. But one will not find many predictions. It is odd not to find predictions in textbooks. Because these theories, even when the modern genetic theory of the mechanism of evolution is used in place of the theory of natural selection, cannot predict what new species will be formed, many persons have thought that these theories do not have predictive value. This is a very erroneous conclusion. The biological literature contains many predictions. You will find some in Science on Trial, The Case for Evolution by D.J. Futuyma (7) and in my paper (8) "Teaching the Theories of Evolution". Futuyma describes a prediction from the descent theory: there will be "only one real evolutionary tree. If this is so, then it should be possible to find different sources of data that all independently give the same evolutionary diagram." We have seen this prediction come true as new data from immunology and molecular biology have supported early classifications based on morphology. In my paper I described a prediction from the theory of natural selection by L.H. Bolley, a plant breeder. Early in this century he predicted he could find a flax plant resistant to the wild disease. He found such a plant and produced disease resistant seeds.

As an aside, a few words about the testing of theories is appropriate here. Theories are usually tested by testing individual postulates, by examining a theory's ability to explain known facts, and by testing predictions. But there is another way of testing broad, general theories. This is by formulating and testing its subtheories. Subtheories make it possible to apply a general theory in limited situations. A subtheory has an additional set of postulates that are more specific, and are consistent with those of its over-theory. Thus the theory of the origin of higher animals in Australia is a subtheory of Darwin's theory of descent with modification and the r-and k- selection theory is a subtheory of the theory of natural selection. The spawning and successful testing of subtheories is a part of research that is common, but is seldom explicitly discussed.

To illustrate the value of having a set of postulates clearly stated and at hand as one reads a theoretical paper, I will use a recent work that I want to understand. This theory is by the previous speaker, Root-Bernstein (9), his **theory of amino acid pairing**. The postulates are:

1. Certain amino acid pairings allow protein-to-protein information transfers.
2. Amino acid pairings are only possible on a beta ribbon.
3. Amino acid pairings involve both the polypeptide backbones and the side chains.
4. For pairings to occur:
   - the backbones must be directionally parallel;
   - the distance between the alpha-carbons must be ca. 5.0 Å;
   - side chains must extend from the backbone on the same side of the paired structure and along the same spacial axis.
5. Side chain pairings are limited
   - to those that do not interfere with the integrity of the beta structure;
   - to those that can interact across the distance between the backbones without steric hindrance;
   - to those permitted by accepted theories of chemical bonding, e.g. hydrophobic residues should be hidden; hydrophilic residues should be free; residues may interact by hydrogen bonding, hydrophobic interactions (van der Waal’s forces), salt bridges, stabilization of ionic charge by interaction with an unsaturated carbon ring;
   - to charge transfer complexes.
6. There are specific criteria for the interaction of amino acid residues with a complementary template (glycine and proline).

Being quite ignorant in this subject, I can see immediately that I will have to pay close attention to what is meant by information transfers, beta ribbon, beta structure, hydrophobic interactions, salt bridges, stabilization of ionic charges, charge transfer complexes, and criteria for the interaction of amino acid residues. If I can get these matters in mind, I may be able to try to evaluate the evidence for the postulates, the explanations, and the predictions and their tests as described by the author.

Since the principles of a science are the major postulates of its theories, what are the principles in the above theories? In the germ theory of disease, the first postulate is the principle: A disease is caused by a parasite growing in the host. Postulate 2 of the descent theory is the principle: Each species arose from another species that preceded it in time. This is the principle of evolution. In the theory of natural selection, natural selection is the principle and this is stated in postulate 9 with a fuller meaning of natural selection present in postulates 7 and 8. Postulate 1 of Root-Bernstein’s theory is the principle of this theory: Certain amino acid pairings allow protein-to-protein information transfers. Why should one bother to give attention to the structure and roles of theories? There are four good reasons for giving attention to theories.

1. Embedded theories give logical structure to established knowledge.
2. The formulation and development of theories is the central and most important activity in the growth of scientific knowledge.
3. Theories are vehicles for collapsing knowledge into its most learnable, manageable, and usable form.
4. Most practical advances today are based on theoretical knowledge.

Science educators are everywhere stating that the public is scientifically illiterate. This view is exemplified in the AAAS book, Science for All Americans (10). Yet the educators are themselves illiterate about the central activity in science and about the structure of the knowledge that this activity has produced for textbooks. Educators do not know in explicit detail the meaning of these words of Einstein, Pauling, and Bruner and then put the understanding to work in their teaching. The response has been slightly above zero. This response is understandable when one recalls the great confusion of meanings attached to "theory" and when one recalls the long tradition of presenting textbook knowledge as a dogmatic "rhetoric of conclusions" (15). Theory structured courses could enhance teaching and learning while at the same time providing right contexts for teaching the pattern, the arts, and the habits of rational thinking.

Biology has clearly been a theoretical science since 1628 when Harvey published his Anatomical Dissertation Concerning the Motion of the Heart and Blood. All the works on classification were theoretical, but were not so acknowledged. Every taxonomist must make assumptions about what characteristics are important and about their relative importance. Every classification scheme is a theory or a system of theories. Early physiology, cytology, and even ecology were highly theoretical, but usually not explicitly so recognized. Today most of the biology on the advancing fronts of knowledge is explicitly theoretical, each theory being a hypothetico-deductive system. Thus biology is a mature science and a mature science has these characteristics as stated by Peter Medawar (16), a Nobel prize winner in the 1960s. "The factual burden of a science varies inversely with its degree of maturity. As a science advances, particular facts are comprehended within, and therefore in a sense annihilated by, general statements of steadily increasing explanatory power and compass-whereupon the facts may be forgotten, for they have no further right to independent existence." The postulates of theories are the "general statements" that make it possible to reduce the "factual burden" of those who are learning the knowledge, of those who are working to increase knowledge by constructing new and better theories, and of those who want to use knowledge to produce practical results.
I believe it would be a great boon to both education and research if all embedded and developing theories were clearly outlined—with their postulates listed, with some examples of lines of reasoning about support, about explanation, and about prediction given, and with a statement about the known or presumed range of applicability. Ecological theories at the general biology level are not too difficult and I am getting them outlined. But advanced theories in ecology are very confusing for a general biologist and I have not yet found a theoretical ecologist who wants to outline all the advanced theories in ecology. Maybe this is a task for a group such as the ecologists in the North Central Forest Experiment Station. If Pasteur was right, an outlining of theories might be very important to forest management in the future. Pasteur (17) said, "Without theory, practice is but routine born of habit. Theory alone can bring forth and develop the spirit of invention." Thus by better organizing and using the rules of nature as they are found and developed in biological theories, man may be able to better manage the biological world to his advantage and to the advantage of the world.

REFERENCES

Ralph W. Lewis, Department of Natural Science, Michigan State University, East Lansing, MI 48824. From a talk delivered at the First North Central Research Workshop of the North Central Forest Experiment Station, USDA Forest Service at Delavan WI, USA. March 29-31, 1993.