Education

Transcending processes and the levels-of-organization concept

Numerous reports have called attention to the major problems and challenges facing science education in the United States (AAAS 1990a, Brown 1989, National Science Board 1986, Rutherford 1989, Sundberg and Dini 1993). It is now widely recognized that students at the college level are frequently deficient in skills necessary for problem solving, critical thinking, and the integration of interdisciplinary concepts (Cameron 1990). Undergraduates increasingly need the opportunity to conduct independent research and to participate in internship experiences if they are to command these skills. In addition, there is an urgent need for undergraduates to develop an environmental literacy as they enter diverse programs in our colleges and universities (Brown 1989, Shamos 1995).

Science classes at the college level often convey common processes (e.g., transfer of energy and conservation of matter) and integrative teaching and research approaches (e.g., scientific method, problem solving, and cost–benefit analysis) in a fragmentary manner. A number of alternative approaches have been suggested to improve scientific teaching in the United States (Allard and Barman 1994, Moore 1993, Tyser and Cerbin 1991, Uno 1990). In this article, we show how attention to transcending functions can provide a new integrative approach that can improve the critical-thinking and problem-solving skills necessary for dealing with long-term, large-scale problems.

Our approach is based on the levels-of-organization concept (Figure 1; MacMahon et al. 1978, Rowe 1961). This is an excellent organizing concept that can be readily adopted for teaching of environmental science and environmental literacy in particular because it provides a basis for analyzing problems across broad temporal and spatial scales (Yeakley and Cale 1991), for understanding hierarchy theory (Allen and Starr 1982, O'Neill et al. 1986), and for integrating the socioeconomic components of resource management in a problem-solving approach (Barrett 1985). A hierarchy is defined here as a graded series of compartments arranged from largest to smallest, but the order could be reversed to start with the lowest level of resolution (Odum 1993).

by Gary W. Barrett, John D. Peles, and Eugene P. Odum

The levels-of-organization concept has long been used to view the natural world in terms of increasing complexity, from the molecular or cellular through the ecosystem or ecosphere levels (MacMahon et al. 1978, Novikoff 1945). The initial use of this concept for understanding biological processes focused on spatial aspects (Rowe 1961). Simon (1962) was the first to recognize the importance of temporal scale in the levels-of-organization concept, thus making it a useful model for understanding hierarchy theory (Allen and Hoekstra 1992, Bossort et al. 1977). Hierarchy theory is a holistic approach addressing the nature and scale of complex questions; it focuses on observation as the interface between perception and learning (Ahl and Allen 1996). An understanding of hierarchy theory is also the basis for the development of a sustainable, noösystem perspective of ecological systems, which takes into account social, economic, and cultural influences (Barrett 1985, 1989). This perspective should contribute to a better understanding of and appreciation for the major environmental problems and issues currently facing society.

The tragedy of fragmentation

In recent years, science has become so fragmented and specialized that the mismatch between traditional academic science disciplines and real-world problems has increased (Carter et al. 1990). Ever-increasing specialization is a recipe for sterility or error—sterility because the comprehensive picture may go unrecognized; error because the specialist may overemphasize the significance of this or that datum in his or her own field (Cluge and Napier 1982). It is more and more the interfaces between disciplines, as well as between levels of organization, that are relevant to solving practical problems. For example, the solution to pollution problems is more likely to come from the interface of ecology and economics than from either discipline acting alone. Accordingly, educators ought to be teaching at the interfaces between disciplines as well as the traditional disciplines themselves (AAAS 1990b). Students also need to appreciate the natural integration of the biotic and abiotic universe. Without this appreciation, students frequently get "turned off" to science in their formative years (AAAS 1990a).

Current modes of learning seldom emphasize that most basic principles, natural laws, mechanisms, and concepts transcend all levels of organization, from cells to the ecosphere. Students are typically taught to consider only a limited range of organizational levels when addressing a particular process or mechanism. Thus, even after completing four years of undergraduate courses in any field of study, students often have great difficulty in comprehending both reductionist and holistic approaches (Barrett 1994, Odum 1977). Barbour (1996) recently pointed out that most professional ecologists also find it difficult to investigate the natural world in a holistic manner. The problem is even more acute for nonscience majors, who often lack the knowledge or skills to address large-scale environmental problems (Lubchenco et al. 1991). Students also need to be provided with opportunities (e.g., internships) to become trained in methodologies (e.g., problem-solving algorithms, cost-benefit analyses, and cybernetics) that are necessary for managing scarce resources (Arrow et al. 1996, Barrett 1985) and for understanding the levels-of-organization approach (Ahl and Allen 1996).

The failure to consider how all levels of organization interact across temporal and spatial scales has limited the ability of students to appreciate and understand biological, physical, and socioeconomic processes that transcend all levels of resolution. Courses in the biological sciences, for example, typically examine multiple levels in isolation (e.g., a course in molecular biology or a course in population biology). By contrast, environmental science courses often begin at the ecosystem or ecosphere levels but terminate at the organism or species level. Unfortunately, students in an introductory course are rarely exposed to all levels due to time, human resource, or budgetary constraints. Compounding this problem, there remains the limited integration of humankind into the ecosystem concept, both in our teaching and investigative approaches, as well as the need to develop interfaces between ecology and the social sciences, humanities, and economics.

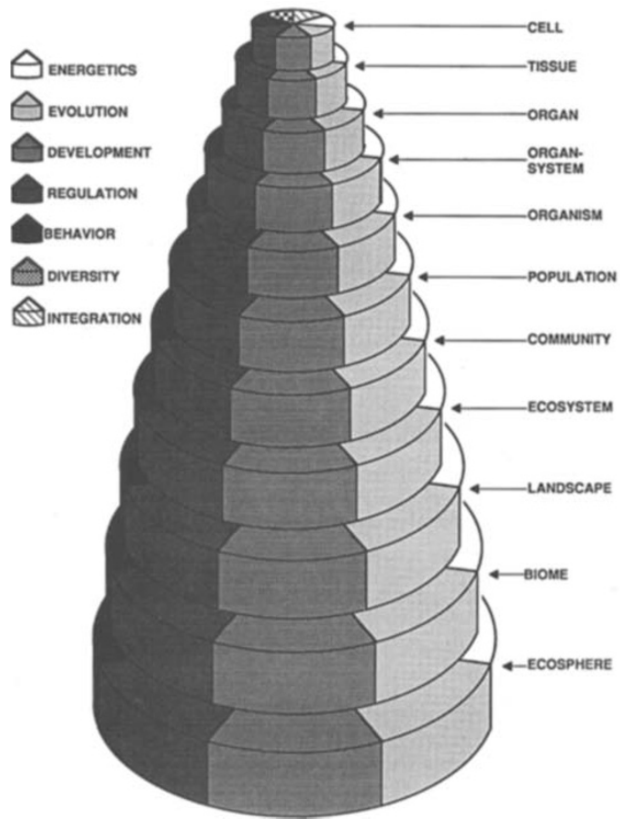

Figure 1. Levels-of-organization concept. Seven transcending concepts or processes are depicted as components of 11 integrative levels of organization.

Transcending approach to the levels-of-organization concept

The levels-of-organization approach is intended to encourage students to understand and investigate biological, ecological, and noöspheric processes across all levels of organization and in an interdisciplinary manner. We believe that an effective approach to teaching environmental science and environmental literacy courses can be developed using the levels-of-organization concept. This approach involves the teaching of principles, natural laws, mechanisms, and processes that transcend all levels of organization (Figure 1). Combining such "transcending" processes with the levels-of-organization concept also would provide a sound perspective for understanding problems across temporal and spatial scales—a prerequisite for dealing with major problems facing society. For example, an understanding of the properties of water, the goods and services provided by water in natural ecosystems, and the global hydrological cycle are all necessary to manage water quality and quantity in a cost-effective and ecologically safe manner at the landscape (watershed) scale.

Our view of the levels-of-organization concept organizes major concepts, principles, natural laws, and regulatory mechanisms into 11 levels of integration (Figure 1). We believe that teaching students how concepts transcend each level of organization encourages a more comprehensive and holistic perspective that is necessary for the development of problem-solving approaches and critical-thinking skills. This perspective will also help to wed reductionist and holistic approaches to higher education. Emphasizing common denominators, such as diversity (e.g., genetic, species, and habitat), will help to make strategies for conserving biologiccal diversity, such as the Sustainable Biosphere Initiative (Lubchenco et al. 1991), more meaningful to both students and the general public. If the citizenry is better informed, then such initiatives are more likely to become policy.

This educational approach can be further developed by viewing the levels-of-organization concept within a hierarchical framework using two levels of understanding (Figure 2). Some concepts or processes, such as energetics, evolution, development, regulation, behavior, diversity, and integration, transcend multiple levels of organization (vertical approach), whereas other concepts or processes pertain to a specific level of organization within a particular discipline or field of knowledge (horizontal approach). Membrane transport, for example, is best studied at the cellular level, whereas net primary productivity is perhaps best investigated at the ecosystem level.

Integrating concepts across levels

We suggest that Figures 1 and 2 serve as models for an introductory course in environmental science and/or environmental literacy. Such a course would include the following transcending processes, concepts, principles, mechanisms, and natural laws:

Energetics. The laws of thermodynamics underpin metabolism at all levels, from cells to the ecosphere.

All students, as well as the general public, must be taught that energy, unlike materials, can not be reused, and that as energy is transformed from one form to another the available quantity declines but the quality (the concentration) may increase—a sort of "bad news–good news" situation. Accordingly, because all systems and all levels are thermodynamically open, a continuous inflow of energy is required. It is also important to teach that energy in some form is always required for the recycling of materials, whether the energetic need be for the Krebs cycle at the cellular level or the hydrologic cycle at the ecosphere level. Thus, there is always a cost to recycling, whether natural or human driven, that must be paid if life and human resource use are to continue (i.e., the net energy principle).

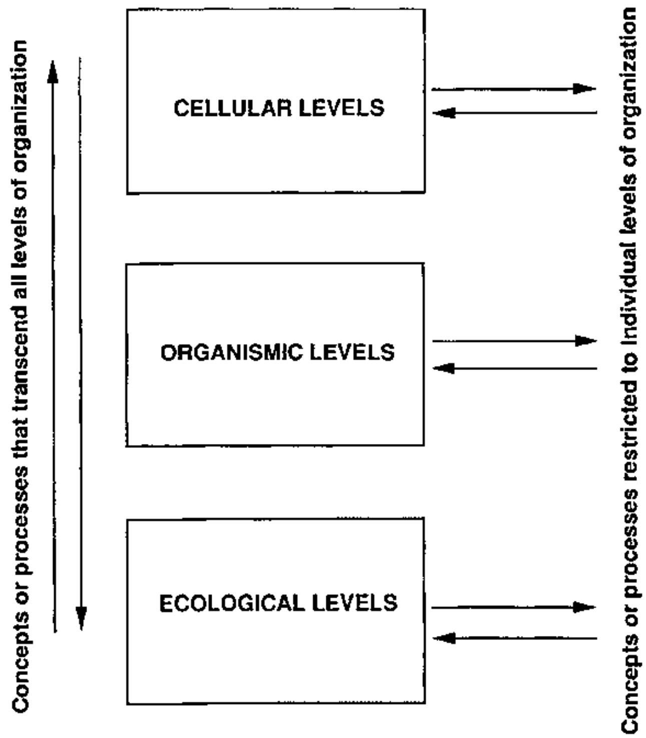

Figure 2. A vertical (levels-of-organization) and horizontal (specialization within levels) approach to understanding natural and human-constructed systems.

Evolution. Students need to understand and appreciate that evolution by natural and artificial selection involves not only genetic changes, which occur at the species level, but also coevolution (e.g., mutualism), which occurs at the community level, and long-term environmental changes, which occur at the landscape level in response to human-caused habitat fragmentation and global climate change. With the rise of biotechnology, humankind now has the power to direct at least certain aspects of evolution. Moreover, everyone needs to understand that nature is full of evolutionary adaptations—an understanding necessary to implement programs such as integrated pest management, disease control, and efficient use of scarce resources. These adaptations can serve as models in fields such as agriculture and forestry, underpinning efforts to reduce the need for excessive use of pesticides and fertilizers that increasingly reduce the quality of water, air, and food.

Development. Growth and development transcend all levels of organization. For example, mitosis is examined at the cellular levels, embryology at the organismic levels, and primary and secondary succession at the ecological levels (Figure 2). An understanding of developmental processes is necessary if humankind is to find cures for cancer, prevent overpopulation, conserve endangered species, restore damaged habitats, and, most important, develop sustainable societies. A good start on integrating growth at different levels is to ask if the sigmoid, or S-shaped growth, model is applicable at all levels compared with the J-shaped growth model. We need to be reminded that the S-shaped form of development encompasses the carrying capacity (K) concept, whereas the J-shaped growth form illustrates exponential growth and lack of regulatory (control) mechanisms. A basic question also seldom asked is not when to grow or not to grow, but when to differentiate. Or, in terms of society, when does humankind go from quantitative to qualitative growth (i.e., when to get better rather than bigger)?

Regulation. Investigating how growth, differentiation, and metabolic processes are regulated at the various levels is important in many contexts—development of cells, body temperature control in organisms, population regulation in ant colonies, the interaction of top-down and bottom-up regulation of food chains, and carbon dioxide–oxygen and other global balances. Although positive and negative feedbacks are involved in regulation at all levels of organization, regulation at higher levels differs from that at the organism level and below in that there are no set-point controls (e.g., a chemostat or thermostat) at the higher levels (Patten and Odum 1981). As a result, pulsing states, rather than steady states, develop above the organism level (Odum et al. 1995). Recognizing this difference could help society to design more realistic ways to deal with air and water quality and other environmental functions that are increasingly important in maintaining human quality of life. So far, society in general has tended mainly to depend on set-point regulation. Society now needs to investigate and better understand regulatory (control) mechanisms operating at higher levels of organization (e.g., relationships between and among trophic levels, chemistry of coevolution, and rates of nutrient recycling).

Behavior. Living systems at all levels evolve behavioral responses to stress and perturbations—responses that enhance survival. Although the study of behavior (ethology) usually focuses on the organism level, the responses of genes and cells, as well as of populations and ecosystems, to perturbations can also be considered to be "behavior." A small or less severe perturbation (e.g., nutrient input) early on may subsidize, or enhance, the system, but later on, an increased input or more severe perturbation may stress the system (i.e., "too much of a good thing"; Odum et al. 1979). At the ecosystem level, for example, it is evident that when the environment is stressful (e.g., temperature or nutrient levels are low), cooperation between individuals and species increases (i.e., more mutualistic behavior develops that enhances survival; Axelrod and Hamilton 1981, Odum 1985). A mutualistic change in human behavior would likely increase the chances of human survival as humankind becomes more crowded and consumptive.

Diversity. The diversity of genes, cells, organisms, and ecosystems is a hallmark of life on Earth and one of the reasons that life has survived and prospered despite periodic catastrophes. It is vital that educators teach the importance of maintaining diversity as a resource (a source of new drugs or other products), as a redundancy (a hedge against environmental changes or hard times), and as a delight to the human spirit (as suggested by the adage "variety is the spice of life"). Diversity is also important as educators, researchers, and citizens attempt to integrate humankind into the levels-of-organization concept. Throughout history, for example, humans have had difficulty dealing with racial and cultural diversity. Students and the general public should be taught that ethnic and cultural diversity is a hallmark of a mature society (just as high species diversity is an attribute of mature ecosystems and landscapes).

Integration. As we move from one level to another, new properties emerge that were not operational at lower levels. For example, when certain coelenterate animal populations join with symbiotic algal populations to form a coral reef, the ecosystem becomes so efficient at recycling and retaining nutrients that it thrives in low-nutrient waters (an emergent property). The emergent properties concept provides an approach to documenting the importance of integration between levels as well as between species. From the human viewpoint, there are also many relationships between autotrophic and heterotrophic systems (Barrett 1985) that are little discussed or poorly understood, such as the interaction between natural solar–powered (alternative agriculture) and human fuel–powered (urban) systems. An integration of these systems should greatly benefit both ecological and economic systems in the future (Barrett et al. 1990). Equally important is the need to find a way to integrate socioeconomic and nonmarket economic values into human society. For example, the restoration and protection of wetlands along streams and rivers will greatly improve water quality, thereby reducing the cost of treatment within urban areas. Perhaps learning how goods and services provided by natural ecological systems (i.e., by nature's capital) can be coupled with those goods and services provided by our socioeconomic systems (i.e., by economic capital) will help humankind with this difficult task.

Importance of the transcending-processes perspective

Issues such as population growth, biotic (e.g., genetic, species, niche, and landscape) diversity, net energy, global climate change, resource management, pollution abatement, and sustainable development can best be approached with an integrated, interdisciplinary perspective in which the scientific, socioeconomic, and political components are addressed in a noöspheric manner (Barrett 1985). We suggest that teachers of courses populated by both nonscience and science majors should start with the transcending processes before going into detailed study of different levels as component units. Providing students, teachers, and members of society with an understanding of a levels-of-organization perspective will encourage the development of problem-solving and critical-thinking skills necessary for addressing long-term and large-scale problems facing society. By implementing these changes in higher education (including the establishment of "retraining programs" for middle and senior educators, researchers, and practitioners from diverse disciplines), we as a society should be better able to develop interfaces between new fields of knowledge, to address large-scale interdisciplinary problems, and to provide a more holistic perspective for establishing a more sustainable society in the future (Barrett 1989, Lubchenco et al. 1991).

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Gary W. Barrett is the Odum Professor of Ecology, John D. Peles is a post-doctoral associate, and Eugene P. Odum is Director Emeritus of the Institute of Ecology, University of Georgia, Athens, GA 30602.

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