Unification in the Century of Biology

Scientific progress is based ultimately on unification rather than fragmentation of knowledge. At the threshold of what is widely regarded as the century of biology, the life sciences are undergoing a profound transformation. They have long existed as a collection of narrow, even parochial, disciplines with well-defined territories. Now they are undergoing consolidation, forming two major domains: one extending from the molecule to the organism, the other bringing together population biology, biodiversity studies, and ecology. Kept separate, these domains, no matter how fruitful, cannot hope to deliver on the full promise of modern biology. They cannot lead to an appreciation of life in its full complexity, from the molecule to the biosphere, nor to the generation of maximal benefits to medicine, industry, agriculture, or conservation biology.

Of course, within each domain, breakthroughs continue to be made, leading to broader understanding. In the first domain, we now discern that causality is indeed continuous across successive levels of organization; for example, we are learning how the composition and dynamics of subcellular molecular machines can explain emergent functions at the cellular level. We are beginning not only to read complex genomes but to understand them functionally by combining diverse approaches: bioinfomatics, high-throughput gene disruption and expression analysis, traditional molecular/cellular/developmental experimentation, and chemical biology and modeling or simulation. Functional genomics is ushering in a quantitative and rigorous systems biology, essentially a new integrative physiology anchored in molecular-level understanding. Insights will be shared across organisms, all the way to humans, because of the unity of life through evolution. Indeed, strong emphasis is already placed on molecular evolution and the evolution of development. Yet the depth of our understanding is curtailed by our inadequate knowledge of evolutionary mechanisms and the extent, distribution, and ecological significance of genetic polymorphisms in natural populations. We are learning a great deal about inbred model organisms in the laboratory and much too little about real species in the wild: humans, pathogens, disease carriers, and agricultural pests.

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Similarly, in the second domain, major advances have illuminated the biology of populations and societies. The phenomena of sexuality, recognition of self and nonself, cooperation, selfishness, predation, symbiosis, and coevolution are fundamental features of life at the level of the organism and beyond and have recently commanded well-deserved attention. However, the analysis has stopped short of attempting to provide mechanistic explanations that are rooted in the other half of biology. The composition, complexity, and dynamics of ecosystems are being analyzed in depth, partly with molecular tools; but the genetic and molecular bases of species interactions and the significance of unexpected sequence identities between species remain unexplained. The important subdisciplines of the second domain have been altogether too loosely coupled to the frontier in the first, and this has compromised their ability to take the next leap forward.

The time is upon us to recognize that the new frontier is the interface, wherever it remains unexplored. Chemical ecology, for example, a discipline emergent from the joint efforts of ecologists and natural products chemists, is now promising to lay bare the fundamentals of chemical communication in nature, as it exploits a newfound alliance with genome biologists. Similarly, what we might call ecopopulation genomics is raising exciting opportunities in the study of mosquito carriers of malaria: Hints from laboratory and population studies suggest that structural mosquito genome polymorphisms, distributed in diverse ecological niches, may help explain observed patterns in disease transmission. In the years to come, innovators will need to jettison the security of familiar tools, ideas, and specialties as they forge new partnerships. Funding agencies will wish to promote interdisciplinary studies, as the National Institutes of Health and National Science Foundation are now doing. Universities will need to rethink institutional structures and curricula, so that both students and scholars will be emboldened to venture across the dissolving disciplinary barriers. The potential, if we seize the amazing new opportunities, is no less than the understanding of life in full.

Fotis C. Kafatos and Thomas Eisner

Fotis C. Kafatos is Director-General of the European Molecular Biology Laboratory, Meyerhofstrasse 1, D-69117 Heidelberg, Germany. Thomas Eisner is in the Department of Neurobiology and Behavior, Cornell University, Ithaca, NY 14853, USA.