Evolution, Science, and Society

Evolutionary Biology and the National Research Agenda

This document is abstracted from a longer version with additional detail. To receive copies of either report, or for more information, please consult our web site via *http://www.amnat.org* or contact one of the Chairs listed below.

Prepared by delegates representing the following scientific societies. These societies have all endorsed the final document.

American Society of Naturalists
Animal Behavior Society
Ecological Society of America
Genetics Society of America
Paleontological Society
Society for Molecular Biology and Evolution
Society for the Study of Evolution
Society of Systematic Biologists

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Evolutionary biology is the study of the history of life and the processes that lead to its diversity. Based on principles of adaptation, chance, and history, evolutionary biology seeks to explain all the characteristics of organisms, and, therefore, occupies a central position in the biological sciences.

Relevance of Evolutionary Biology to the National Research Agenda

The twenty-first century will be the "Century of Biology." Driven by a convergence of accelerating public concerns, the biological sciences will be increasingly called on to address issues vital to our future well-being: threats to environmental quality, food production needs due to population pressures, new dangers to human health prompted by the emergence of antibiotic resistance and novel diseases, and the explosion of new technologies in biotechnology and computation. Evolutionary biology in particular is poised to make very significant contributions. It will contribute directly to pressing societal challenges as well as inform and accelerate other biological disciplines.

Evolutionary biology has unequivocally established that all organisms evolved from a common ancestor over the last 3.5 billion years; it has documented many specific events in evolutionary history; and it has developed a well-validated theory of the genetic, developmental, and ecological mechanisms of evolutionary change. The methods, concepts, and perspectives of evolutionary biology have made and will continue to make important contributions to other biological disciplines, such as molecular and developmental biology, physiology, and ecology, as well as to other basic sciences, such as psychology, anthropology, and computer science.

In order for evolutionary biology to realize its full potential, biologists must integrate the methods and results of evolutionary research with those of other disciplines both within and outside of biology. We must apply evolutionary research to societal problems, and we must include the implications of that research in the education of a scientifically informed citizenry.

To further such goals, delegates from eight major professional scientific societies in the United States, whose subject matter includes evolution, have prepared this document. It includes contributions by other specialists in various areas. Feedback on earlier drafts was elicited from the community of evolutionary biologists in the United States, and the draft was made public on the World Wide Web. The delegates arrived at a series of recommendations that address the areas that follow.

Advancing Understanding through Research

To capitalize on evolutionary biology as an organizing and integrating principle, we urge that:

- evolutionary perspectives be incorporated as a foundation for interdisciplinary research to address complex scientific problems
- evolutionary biologists work toward building meaningful links between basic research and practical application
- evolutionary biology play a more explicit role in the overall mission of federal agencies that could benefit from contributions made by this field

Advancing Understanding through Education

We encourage major efforts to strengthen curricula in primary and secondary schools, as well as in colleges and universities, including:

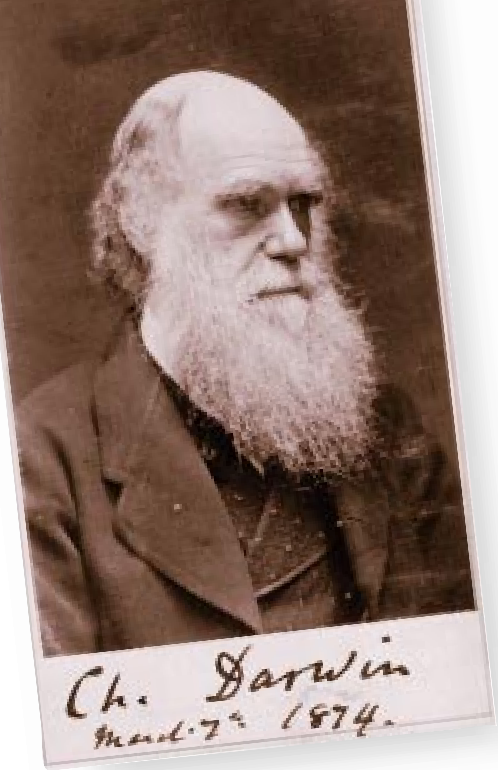
- support of supplemental training for primary school teachers and/or midcareer training for secondary school science teachers in evolutionary biology
- greater emphasis on evolution in undergraduate college curricula for biology majors and premedical students, with accessible alternative courses for nonmajors
- integration of relevant evolutionary concepts into the postbaccalaureate training of all biologists and of professionals in areas such as medicine, law, agriculture, and environmental sciences

Advancing Understanding through Communication

We urge the following roles for evolutionary biologists:

- communicating to federal agencies, and to other institutions that support basic or applied research, the relevance of evolutionary biology to the missions of these organizations
- training the next generation of evolutionary biologists to be aware of the relevance of their field to societal needs
- informing the public about the nature, progress, and implications of evolutionary biology

FOUNDATIONS OF



PHYLOGENETIC ANALYSIS. Recent advances in DNA sequencing and computation permit precise reconstruction of evolutionary relationships among species. For example, molecular data have enabled deeper understanding of the evolutionary origins of the local species of the silverswords, a group of plants endemic to Hawaii.

MORPHOLOGICAL AND MOLECULAR VARIATION. Variation is a key feature of evolution. Differentiation in bill form among related species of honeycreepers provides insight into evolutionary adaptation for feeding. Molecular variation provides insight into genetic processes underlying evolutionary change.

EVOLUTION BY NATURAL SELECTION. Nineteenth-century biologists Charles Darwin and Alfred Russell Wallace established the foundations for evolutionary theory.

ADAPTATION, CHANCE, AND

What Is Evolution?

Biological evolution consists of change in the hereditary characteristics of groups of organisms over the course of generations. From a long-term perspective, evolution is the descent with modification of different lineages from common ancestors. From a short-term perspective, evolution is the ongoing adaptation of organisms to environmental challenges and changes. Thus evolution has two major components: the branching of lineages and changes within lineages.

What Are the Goals of Evolutionary Biology?

Evolutionary biology seeks to explain the diversity of life: the variety of organisms and their characteristics, and their changes over time. Evolutionary biology also seeks to interpret and understand organismal adaptation to environmental conditions. The two encompassing goals of evolutionary biology are to discover the history of life on earth and to understand the causal processes of evolution. Insights achieved through efforts to meet these goals greatly enhance our understanding of biological systems.

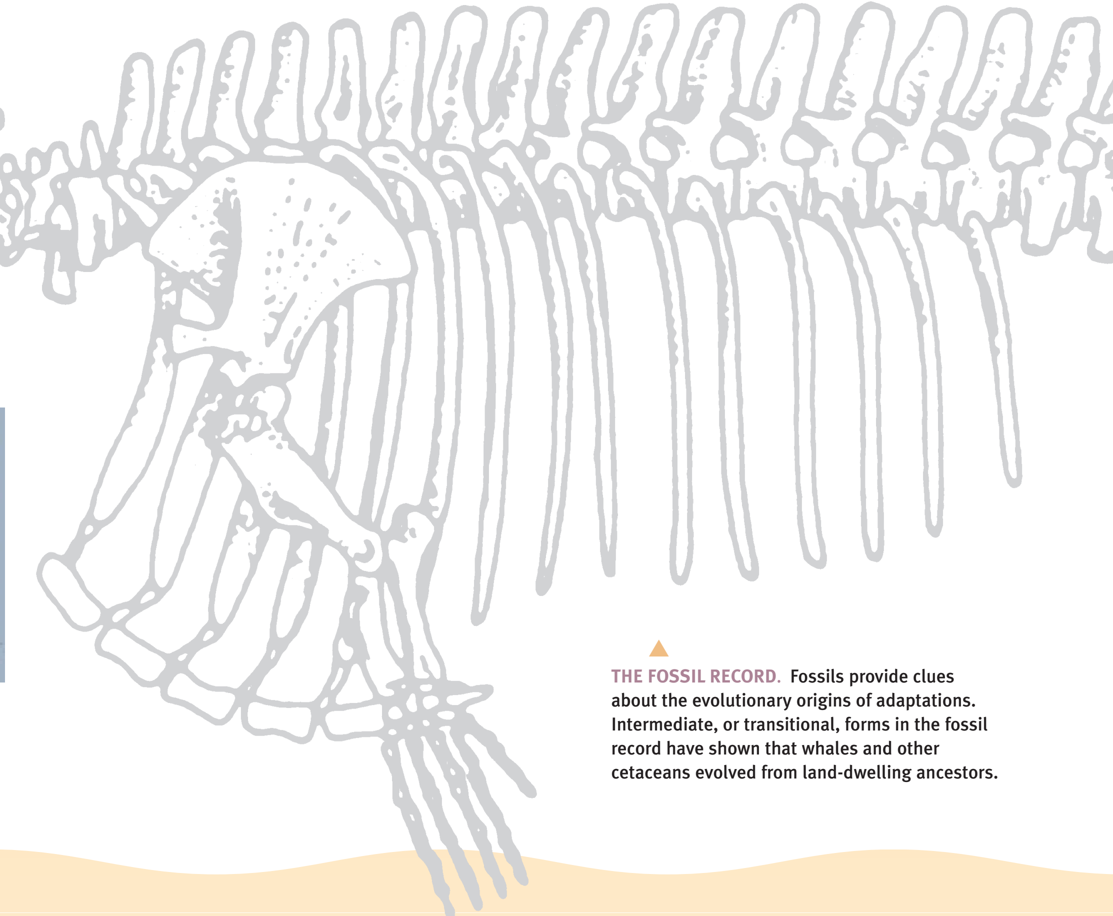
Evolutionary biologists often work at the interface of many subdisciplines of biology, leading to the development of subject areas such as behavioral evolution, evolutionary developmental biology, evolutionary ecology, evolutionary genetics, evolutionary morphology, evolutionary systematics, and molecular evolution. The subdisciplines of evolutionary biology also have formed direct links with fields such as statistics, economics, geology, anthropology, and psychology.

How Is Evolution Studied?

Evolutionary biology draws on a wide range of methodologies and conceptual approaches.

Methods for understanding the history of evolution include observations of the fossil record and categorization and classification of variations among living organisms. Differences and similarities among species in anatomy, genes, and other features can be analyzed by molecular and statistical methods that enable us to estimate historical relationships among species and the sequence in which their characteristics evolved.

EVOLUTIONARY BIOLOGY



HISTORY

THE FOSSIL RECORD. Fossils provide clues about the evolutionary origins of adaptations. Intermediate, or transitional, forms in the fossil record have shown that whales and other cetaceans evolved from land-dwelling ancestors.

Studies of ongoing evolutionary change employ observation and experimentation. Analysis of genetic variation enables us to characterize mutation, genetic drift, natural selection, and other processes of evolution. The “comparative method” contrasts features of species that have adapted to different environments. Sophisticated mathematical models and analyses are frequently employed for both description and predication.

Why Is Evolutionary Biology Important?

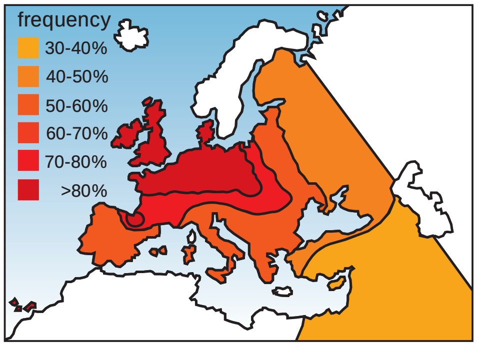
Evolutionary biology provides the key to understanding the principles governing the origin and extinction of species. It provides causal explanations, based on history and on processes of genetic change and adaptation, for the full sweep of biological phenomena, ranging from the molecular to the ecological. Thus, evolutionary biology allows us to determine not only how and why organisms have become the way they are, but also what processes are currently acting to modify or change them.

Response to change is a feature of evolution that is becoming increasingly important in terms of scientific input into societal issues. We live in a world that is undergoing constant change on many levels, and much of that change is a direct consequence of human activity. Evolutionary biology can contribute explicitly to enhanced awareness and prediction of mid- and long-term consequences of environmental disturbances, whether they be deforestation, application of pesticides, or global warming.

Distinctive perspectives on biology offered by evolutionary biology include emphasis on the interplay between chance and adaptation as conflicting agents of biological change, on variation as an inherent feature of biological systems, and on the importance of biological diversity. Variation is a key concept, since evolutionary change ultimately depends on the differential success of competing genetic lineages. The ultimate consequence of variation and evolutionary divergence is biological diversity.

Biological species are not fixed entities, but rather are subject to ongoing modification through chance or adaptation. Understanding why and how some species are able to change apace with new environmental challenges is critical to the sustainability of human endeavor.

APPLICATIONS THAT AFFEC



EVOLUTION OF HUMAN GENETIC DISORDERS. Some genetic diseases, such as cystic fibrosis, are caused by mutations that occur at high frequencies in certain human populations in Europe. Evolutionary geneticists are working to understand how natural selection keeps deleterious genes at such high frequencies. Their findings may lend insight to the broader physiological impacts of the cystic fibrosis gene.

CONSERVATION GENETICS. Evolutionary analysis reveals extremely low levels of genetic diversity among living cheetah, likely due to a dramatic population decline—and associated inbreeding—thousands of years ago. This hinders the cheetah's ability to reproduce successfully, which threatens the species' survival. Such information is being used to develop management recommendations for this endangered species.

MEETING SOCIETY'S

How Does Evolutionary Biology Contribute to Society?

In addition to the historical dimension, evolution is an important feature in our everyday lives. Evolution is happening all around us: in our digestive tracts, in our lawns, in woodland lots, in ponds and streams, in agricultural fields, and in hospitals. For short-lived organisms such as bacteria and insects, evolution can happen on a very short time scale. This immediacy brings evolutionary biology directly into the applied realm. Indeed, evolutionary biology has a long history and a bright future in terms of its ability to address pressing societal needs. Evolutionary biology has already made particularly strong contributions in the following areas:

Environment and conservation. Evolutionary insights are important in both conservation and management of renewable resources. Population genetic methods are frequently used to assess the genetic structure of rare or endangered species as a means of determining appropriate conservation measures. Studies of the genetic composition of wild relatives of crop species can be used to discover potentially useful new genes that might be transferred into cultivated species. Studies of wild plants' adaptations to polluted or degraded soils contribute to the reclamation of damaged land.

Agriculture and natural resources. The principles of plant and animal breeding strongly parallel natural evolutionary mechanisms, and there is a rich history of interplay between evolutionary biology and agricultural science. Evolutionary insights play a clear role in understanding the ongoing evolution of various crop pathogens and insect pests, including the evolution of resistance to pest-control measures. The methods of evolutionary genetics can be used to identify different gene pools of commercially important fish and other organisms, their migration routes, and differences in their physiology, growth, and reproduction.

Finding useful natural products. Many thousands of natural products are used in medicine, food production and processing, cosmetics, biotechnology, pest control, and industry, but millions of other potentially useful natural products have yet to be screened or even discovered. Evolutionary principles allow a targeted search by predicting adaptations to environmental selection pressures and by

T OUR LIVES

NATURAL PRODUCTS FROM POISON FROGS. Knowledge of evolutionary relationships has helped to guide research scientists to the discovery of new natural compounds from Central and South American poison frogs. Potential biomedical applications include heart-stimulating activity and use in painkillers.

GENETIC RESOURCES FOR CROP IMPROVEMENT. Evolutionary relationships between crops and wild relatives provide insight into potentially useful genes for crop improvement.

NEEDS

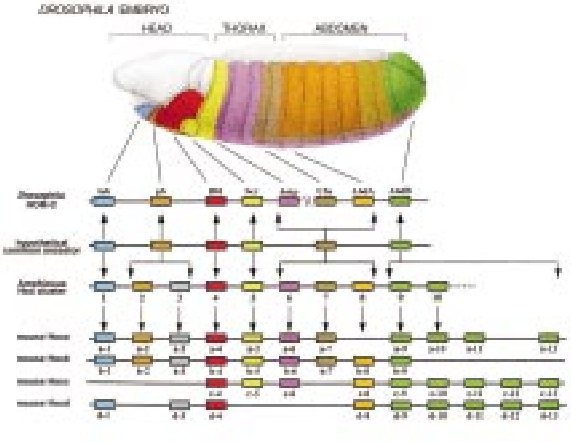
identifying organisms related to those that have already yielded useful natural products. Exploration of related species also has made it possible to develop natural products from more accessible relatives of rare species in which natural products have been found, as occurred when the rare and endangered Pacific yew was found to contain a substance that led to development of a drug (tamoxifen) useful in treating breast cancer.

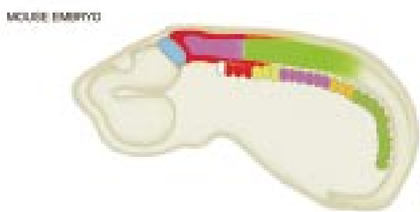
Human health and medicine. Methods and principles from evolutionary biology have contributed to understanding the links between genes and human genetic diseases, such as cystic fibrosis. Evolutionary methods help to trace the origins and epidemiology of infectious diseases, and to analyze the evolution of antibiotic resistance in pathogenic microorganisms. Evolutionary principles are used to interpret human physiological functions and dietary needs. Methods developed by evolutionary geneticists are playing an important role in mapping defective human genes, in genetic counseling, and in identifying genetic variants that alter risks for common systemic diseases and responses to medical treatments.

Biotechnology. The interplay between biotechnology and evolutionary biology holds great promise for application to important societal needs. As genetic engineering has reached the field implementation stage, evolutionary biologists have been prominently involved in risk assessment as well as interpretation of phenotypic consequences of transgene insertion. Finally, the automation of DNA sequencing has made it possible to reconstruct the precise genealogical relationship among specific genes, such as those of the human immunodeficiency virus (HIV).

Understanding humanity. Evolutionary biology has contributed greatly to human understanding of ourselves by describing our origins, our relationships to other living things, and the history and significance of variation within and among different groups of people. Evolutionary anthropologists, psychologists, and biologists have advanced hypotheses on the biological bases of human culture and behavior. In addition, the evolutionary framework for understanding humanity has had a profound impact on literature, the arts, philosophy, and other areas of the humanities.

CONTRIBUTIONS IN BIOL





DEVELOPMENTAL BIOLOGY. Recent studies of many different types of animals suggest that much of animal diversity has evolved by changes in a common set of regulatory genes. The organization of such regulatory genes has been studied in detail in model organisms, such as fruit flies, and parallel genetic effects have been identified in a wide range of organisms.

THE TREE OF LIFE. Advances in molecular, morphological, and computational approaches have enabled the emergence of a comprehensive framework for the evolutionary history of all life on earth. The Tree of Life project provides a unified network for systematic investigation on all levels.

ADVANCING HUMAN

How Does Evolutionary Biology Contribute to Basic Science?

Evolutionary biology has far-reaching scientific impact. Among their accomplishments in studying the history and processes of evolution, evolutionary biologists have:

- established that all organisms have evolved from a common ancestor over more than 3.5 billion years of earth's history
- developed methods of inferring phylogenetic, or genealogical, relationships among organisms
- described patterns of diversification and extinction in both the fossil record and contemporary ecosystems
- developed and tested general theories that account for the evolution of phenotypic traits, including complex characters such as cooperative behavior and senescence
- made substantial progress in understanding evolution at the molecular level
- elucidated many aspects of human evolution

Contributions to Other Biological Disciplines

Evolution is central to biological understanding. Biologists in diverse fields regard at least a portion of what they do as evolutionary. Recent accomplishments to which evolutionary biology has contributed include the following:

Molecular biology. Evolutionary approaches have contributed insight into the function and structure of molecular processes within cells. Examples include reconstruction and functional analysis of ancestral protein sequences, and elucidation of the significance of different types of DNA. Evolutionary research thus points the way to research on fundamental molecular mechanisms.

Developmental biology. A resurgence in interaction between developmental biology and evolutionary biology is now under way, in part through comparisons among families of genes that play critical roles in development. For example, the same genes in organisms as different as insects and

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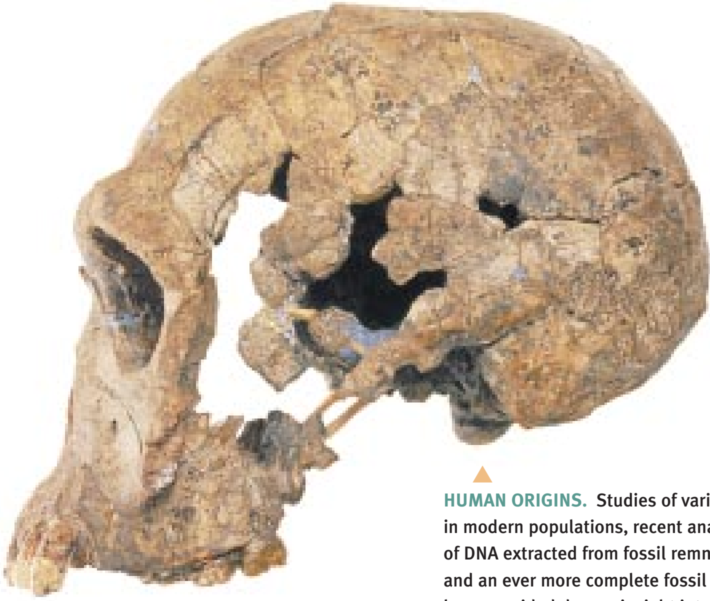
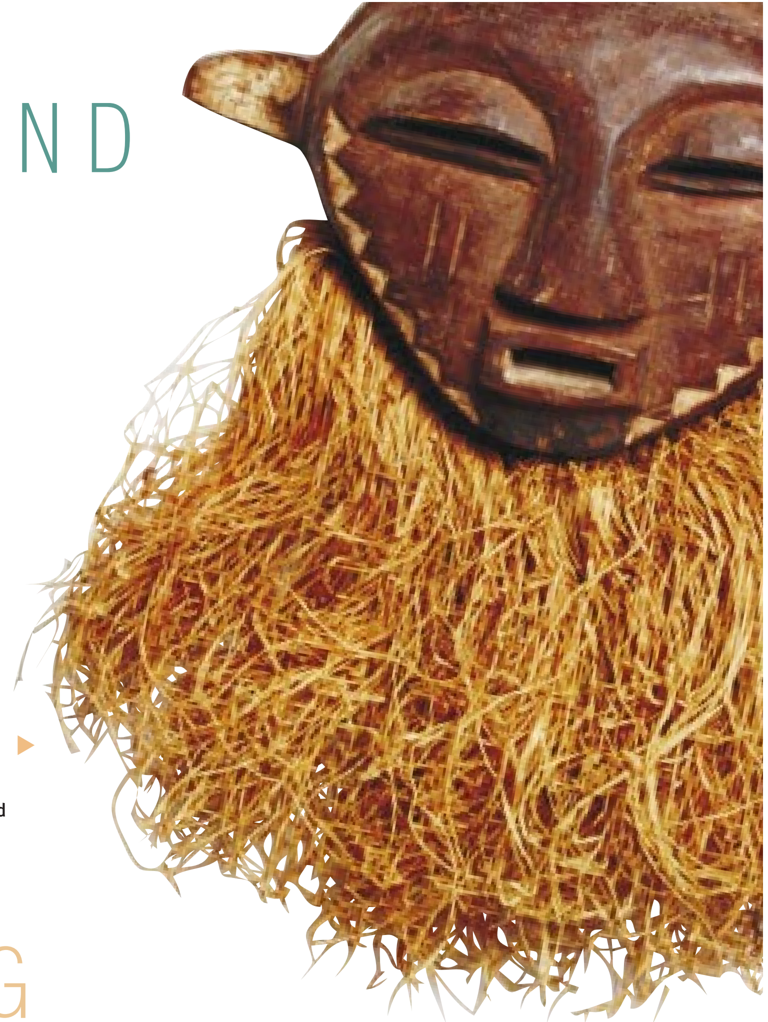


HUMAN ORIGINS. Studies of variation in modern populations, recent analysis of DNA extracted from fossil remnants, and an ever more complete fossil record have provided deeper insight into the evolutionary emergence of modern humans and their culture.



UNDERSTANDING

mammals play surprisingly similar developmental roles in some instances, and different roles in other cases. Such studies help to identify the developmental functions of genes and lead to a deeper understanding of the processes that transform a fertilized egg into a complex adult.

Physiology and anatomy. Evolutionary biology has long influenced the study of physiology and anatomy in animals and plants, and has the potential to make many other contributions that only now are being developed. Some of these contributions will affect the study of human physiology, including related areas such as clinical psychology. The logical perspectives, methods, and comparative data of evolutionary biology can advance our understanding of functional anatomy and physiological mechanisms, and can be applied to areas such as medicine, agriculture, and veterinary science.

Neurobiology and behavior. From its inception, the field of animal behavior has had a strong evolutionary base, for its goals have included understanding the evolutionary origin of behavioral traits and their adaptiveness. The evolutionary study of animal behavior has joined with comparative psychology in several areas of research, such as the study of learning and the search for adaptive mechanisms in human cognitive processes.

Applications beyond biology. There have long been rewarding interactions between evolutionary biology and other analytical fields, notably statistics and economics. Some of the basic tools in statistics, including analysis of variance and path analysis, were originally developed by evolutionary biologists. Along the same lines, evolutionary algorithms that mimic natural selection in biological systems are currently being used in computer and systems applications.

What Does the Future Hold for Evolutionary Biology?

Researchers in molecular and developmental biology, physiology, ecology, animal behavior, psychology, anthropology, and other disciplines continue to adopt the methods, principles, and concepts of evolutionary biology as a framework. Likewise, applied research in forestry, agriculture, fisheries, human genetics, medicine, and other areas has increasingly attracted scientists trained in evolutionary biology. Evolutionary biologists have expanded their vision, addressing both basic questions throughout the biological disciplines and problems posed by society's needs. As a result of both the rapid growth of this "evolutionary work force" and technological advances in areas such as molecular methodology, computing, and information processing, progress in evolutionary biology and related areas is more rapid now than ever before. With appropriate and necessary support in education and research, the evolutionary disciplines will make ever greater contributions to applied and basic knowledge.

Applied Science

In the applied realm, evolutionary biologists are embracing their social responsibilities. There are many ways in which their scientific efforts can help humanity:

- to understand and combat genetic, systemic, and infectious diseases
- to understand human physiological adaptations to stresses, pathogens, and other causes of ill health
- to improve crops and mitigate damage by pathogens, insects, and weeds
- to develop tools for analyzing human genetic diversity as it applies to health, law, and the understanding of human behavior
- to use and develop biological resources in a responsible manner
- to remedy damage to the environment
- to predict the consequences of global and regional environmental change
- to conserve biodiversity and discover its uses

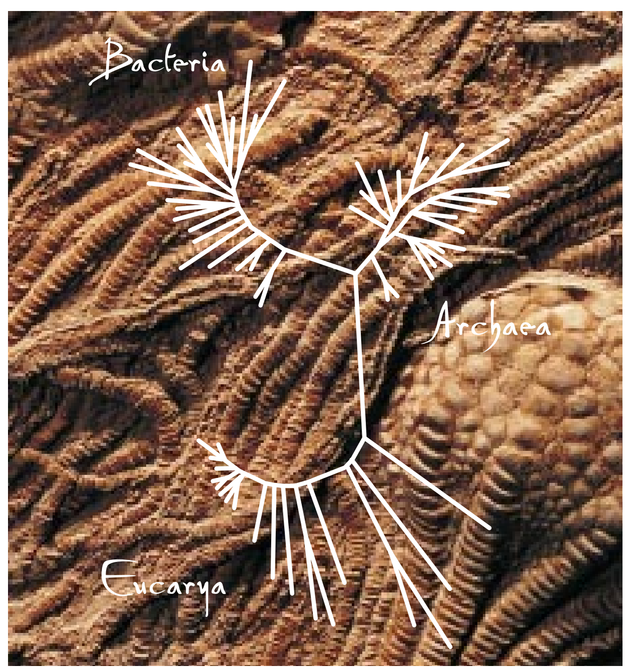
Basic Science

In basic science, we stand at the threshold of:

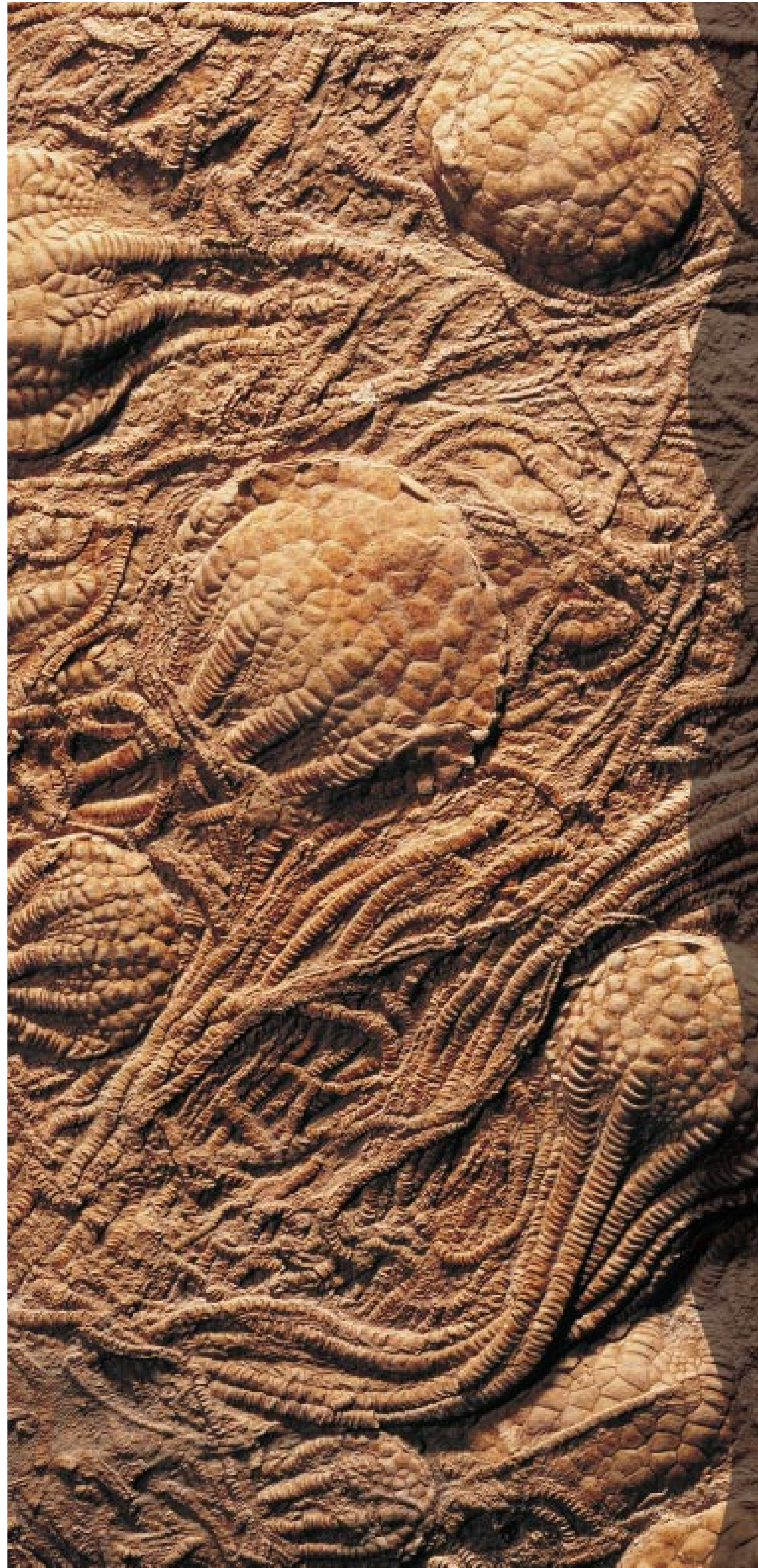
- fully documenting biodiversity and describing the phylogenetic relationships among all organisms
- more completely understanding the causes of major changes in the history of life
- discovering and explaining processes of evolution at the molecular level
- understanding how developmental mechanisms evolve and give rise to new anatomical structures
- elucidating the processes that both cause and constrain adaptations in physiology, endocrinology, and anatomy
- deriving a deeper understanding of the adaptive meaning and mechanisms of behavior
- developing a predictive theory of coevolution among species, such as pathogens, parasites, and their hosts, and of the effects of coevolution on populations and ecological communities

Conclusion

Evolutionary biology plays a central role in the complexity of biological systems. Evolution is the source of biocomplexity. The continued and enhanced support of this field is critical to maximizing the nation's research progress in both basic and applied arenas. In terms of societal needs for the twenty-first century, the time to make the investment in evolutionary biology is now, while there is still time either to change current trends or to better prepare us to deal with their consequences. Current and projected population levels will result in increasing environmental impacts, increasing pressure on food production, ever greater challenges to biological diversity, and enhanced opportunities for the emergence of new diseases. A healthy scientific base in evolutionary biology is an essential element in preparing us to address these issues. Evolutionary biology must be at the heart of the nation's research agenda in biology, just as it is at the heart of the field of biology.



Universal phylogenetic tree showing the relationships among Bacteria (e.g. most bacteria and blue-green algae), Archaea (e.g. methanogens and halophiles) and Eucarya (e.g. protists, plants, animals, and fungi).



Cover

Mark Spencer/Auscape. Reef scene of sea fans, crinoids, and soft corals, Coral Sea, Australia

Deane Bowers, University of Colorado–Boulder. Baltimore Checkerspot butterfly *(Euphydryas phaeton)*, Eastern United States

DNA, Rutgers University photo archives

Jonathan Adrain, Natural History Museum, London. Whiterock fauna (Lower Silurian Period) fossil trilobite *(Exallaspis coronata)*, W. Midlands, England

Mary E. Eaton/NGS Image Collection. Devil's bit *(Chamaelirium luteum)*. Reproduced with permission from *The Book of Wild Flowers*. ©1924, National Geographic Society

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John Weinstein, Field Museum of Natural History, and David Jablonski, University of Chicago. Fossil crinoids, Cretaceous Period (85 million years old), Kansas

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Julie Margaret Cameron, c/o Clements Museum, University of Michigan. *Carte de visite* photograph of Charles Darwin (1874)

Bruce Baldwin, University of California–Berkeley. Mauna Kea silversword *(Argyroxiphium sandwicense* subsp. *sandwicense)*, Wailuku drainage, Hawaii

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R. Kellogg, c/o Annalisa Berta, San Diego State University. Line drawing of archaeocete (fossil whale) skeleton. Abstracted with permission from A. Berta, 1994. *What Is a Whale? Science* 263:180. ©1994, American Association for the Advancement of Science

H. Douglas Pratt, c/o Lenny Freed, University of Hawaii. Hawaiian honeycreeper bill variation

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Aravinda Chakravarti, Case Western Reserve University. Cystic fibrosis gene frequency map

Karl Ammann, c/o NOAHS Center, National Zoological Park. Cheetah

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Charles W. Myers, American Museum of Natural History. Poison-dart frog *(Phyllobates terribilis)*, Colombia, South America

Charles Rick, University of California–Davis. Cultivated tomato and its wild relatives

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Sean B. Carroll, University of Wisconsin. *Hox* gene organization and expression in *Drosophila* and mouse embryos. Reproduced with permission from S.B. Carroll et al., 1995. *Homeotic genes and the evolution of arthropods and chordates. Nature* 376:479-485. ©1995, Macmillan Magazines Ltd.

David Maddison, University of Arizona. Tree of Life logo

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National Museum of Kenya, c/o Craig S. Feibel, Rutgers University. 1.9-million-year-old hominid skull *(Homo habilis)*, Koobi Fora, Rift Valley, Africa

African mask, Rutgers University photo archives

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Norman R. Pace, University of California–Berkeley. Universal phylogenetic tree based on ribosomal RNA sequence differences. Abstracted with permission from N.R. Pace, 1997. *A Molecular View of Microbial Diversity and the Biosphere. Science* 276:734-740. ©1997, American Association for the Advancement of Science