Edward O. Wilson

Consilience Among the Great Branches of Learning[1]

THE CENTRAL THEME OF THE ENLIGHTENMENT, enhanced across three centuries by the natural sciences, is that all phenomena tangible to the human mind can be rationally explained by cause and effect. Thus humanity can—all on its own—know; and by knowing, understand; and by understanding, choose wisely.

The idea is amplified by what Gerald Holton has called the Ionian Enchantment, the conviction that all tangible phenomena share a common material base and are reducible to the same general laws of nature.[2] The roots of the Enchantment reach to the beginnings of Western science in the sixth century B.C., when Thales of Miletus, in Ionia, considered by Aristotle to be the founder of the physical sciences, proposed that all substances are composed ultimately of water. Although the hypothesis was spectacularly wrong, the ambition it expressed—to attain the broadest possible generalization in cause-and-effect explanations—was destined to become the driving force of Western science.

The success of the scientific revolution may make this perception now appear trivially obvious. Surely, it will seem to many, coherent cause-and-effect explanation is an inevitable consequence of logical thought. But to see otherwise it is only necessary to examine the history of Chinese science. From the first through the thirteenth centuries, as Europe passed from late antiquity through the Dark Ages, science in China flourished. It kept pace with Arab science, even though geographic isolation deprived Chinese scholars of the

Edward O. Wilson is Research Professor and Honorary Curator in Entomology at Harvard University.

ready-made base that Greek culture provided their Western counterparts. The Chinese made brilliant advances in subjects such as descriptive astronomy, mathematics, and chemistry. But they never acquired the habit of reductive analysis in search of general laws that served Western science so well from the seventeenth century on. They consequently failed to expand their conception of space and time beyond what was attainable by direct observation with the unaided senses. The reason, according to Joseph Needham, the principal Western chronicler of the subject, was their emphasis on the holistic properties and harmonious relationships of observable entities, from stars to trees to grains of sand.[3] Unlike Western scientists, they had no inclination to search for abstract codified law in nature. Their reluctance was stimulated to some degree by the historic rejection of the Legalists, who attempted to impose rigid, quantified law during the transition from feudalism to bureaucracy in the fourth century B.C. But of probably greater importance was the fact that the Chinese steered away from the idea of a supreme being who created and supervises a rational, law-governed universe. If there is such a ruler in charge, it makes sense—Western sense at least—to read a divine plan and code of laws into physical existence. If, on the other hand, no such ruler exists, it seems more appropriate to search for separate rules and harmonious relations among the diverse entities composing the material universe. In summary, it can be said that Western scholars but not their Chinese counterparts hit upon the more fortunate metaphysics among the two most available to address the physical universe.

Western scientists also succeeded because they believed that the abstract laws of the various disciplines in some manner interlock. A useful term to capture this idea is *consilience*. The expression is more serviceable than coherence or interconnectedness because the rarity of its usage has preserved its original meaning, whereas coherence and interconnectedness have acquired many meanings scattered among a plethora of contexts. William Whewell, in his 1840 synthesis *The Philosophy of the Inductive Sciences*, introduced consilience as literally a "jumping together" of facts and theory to form a common network of explanation across the scientific disciplines. He said, "The Consilience of Inductions takes place when an Induction, obtained from one class of facts, coincides with an Induction, obtained from another different class. This Consilience is a test of the truth of the Theory in which it occurs."

Consilience proved to be the light and way of the natural sciences. Physics, with its astonishing congruity to mathematics, came to undergird chemistry, which in turn proved foundational for biology. The successful union was not just a broad theoretical consistency, as articulated by Whewell, but an exact folding of principles pertaining to more complex and particular systems into the principles for simpler and more general systems. Organisms, it came to pass, can be reduced to molecules whose properties are entirely conformable to the laws of chemistry, and the elements to which the molecules are composed are in turn conformable to the laws of quantum physics.

To place the organization of modern science in clearer perspective, the disciplines can be tied to the position that their entities occupy in the scale of space and time, while noting that each class of entities represents a level of organization determined by the ensemble of other entities composing them and located lower on the space-time scale.

The consilient view of the natural world is illustrated by the use of the space-time scale to define the disciplines of biology:

Evolutionary space-time. Over many generations entire populations of organisms undergo evolution, which at the most elemental level is a change in the frequencies of the genes in the organisms that compose the populations. The foremost cause of evolution is natural selection, the differential survival and reproduction of the competing genes—or, put more precisely, the differential survival and reproduction of the organisms whose traits are determined by the genes. Natural selection occurs when populations interact with their environment. The subdiscipline broadly covering the phenomena in this segment of space-time is evolutionary biology.

Ecological space-time. Evolution by changes in gene frequency is coarse grained: It becomes apparent only when the history of an entire population is watched across generations. The process of natural selection driving it is finer grained, comprising particular events that affect the birth, reproduction, and death of individual organisms. These are events that can be observed only in a more constricted space and during shorter periods of time, usually the span of a season or less, than is the case for genetic evolution. They are addressed by the discipline of ecology. (Ecology is often put under the rubric of evolutionary biology, when that subject is broadly defined.)

Organismic space-time. Natural selection acts on the anatomy, physiology, and behavior of organisms whose programs of development are prescribed by genes. These properties usually occupy millimeters to meters in space and seconds to hours in time. The subdiscipline treating them is organismic biology.

Cellular space-time. The anatomy, physiology, and behavior of organisms are aggregated phenomena of cells and tissues. Covering micrometers to centimeters, and milliseconds to full generations, they are the province of cellular and developmental biology.

Biochemical space-time. The development and function of cells and tissues are themselves the aggregate products of highly organized systems of molecules. At this latter level, space ranges from nanometers to millimeters, and time usually from nanoseconds to minutes. The responsible discipline is molecular biology.

Two superordinate ideas unite and drive the biological sciences at each of these space-time segments. The first is that all living phenomena are ultimately obedient to the laws of physics and chemistry, with higher levels of organization arising by aggregate behavior at lower levels. The second is that all biological phenomena are products of evolution, and principally evolution by natural selection. The two ideas are expressions of consilience in the following way: Cells and thence organisms, being organized ensembles of molecules, are physicochemical entities, which were assembled not at random but by natural selection. Looked at this way, consilience in biology is the full sweep through the space-time scale, from near-instantaneous molecular process to the transgenerational shifts of gene frequency that compose evolution.

To many critics, especially in the social sciences and humanities, such an extreme expression of reductionism will seem fundamentally wrong-headed. Surely, they will say, we cannot explain something as complex as a brain or an ecosystem by molecular biology. To which most biologists are likely to respond, yes, we can, or we will be able to do so within a few years. The critics in turn call that impossible; such complex systems are distinguished by holistic, emergent properties not explicable by molecular biology, let alone atomic physics. The only fair response to this is yes, put that way, you are right.

Thus arises the paradox of emergence: Complex biological phenomena are reducible but cannot be predicted from a knowledge of molecular biology, at least not contemporary molecular biology. Each higher level of organization requires its own principles, including precisely definable entities, processes, spatial relationships, interactive forces, and sensitivity to external influences, which permit an accurate characterization and perhaps a stab at prediction from knowledge of its elements. Still, the principles, if sound, can be reduced from the top down and stepwise to those formulated at lower levels of organization. An ecosystem, to take the most complicated of all levels, can be broken into the species composing its biota. The species in turn can be analyzed according to the demography of the organisms composing them (population size and growth, birth and death schedules, age structure), along with their interactions with other kinds of organisms and with the physical environment. As part of this study, the organisms can be divided into organ systems, the organ systems into tissues and cells, and so on. The ecosystem, like other biological systems, is not truly hierarchical but heterarchical. It is constrained by the nature of its elements, and the behavior of the elements is determined at least in part by the sequences and proportions in which they are combined. By and large, however, the entities of each level can be reduced; and the principles used to describe the level, if apposite and correct, can be telescoped into those of lower levels and, especially, the next level down. That in essence is the process of reduction, or top-down consilience, which has been intellectually responsible for the enormous success of the natural sciences.

To proceed in the opposite direction, bottom-up, by synthesis—simple to more complex, general to more specific—is far more difficult. Physical scientists have succeeded splendidly at the task. They have interwoven principles of quantum theory, statistical mechanics, and reagent chemistry into stepwise syntheses from subatomic particles to atoms to chemical compounds. Advances in biology, if we measure their success by predictive power, have been much slower. Scanning the space-time scale along which biological complexity increases, we can see progress decelerate to a near stall at the level of protein synthesis. This is a critical juncture in the life sciences. About one hundred thousand kinds of protein molecules are found in the body of a vertebrate animal. Along with the nucleic acids that encode them, they are the essential materials of life. In particular, proteins form most of the basic structure of the body while running its machinery through catalysis of organic chemical reactions. Thanks to advances in technology, biochemists find it relatively easy to sequence the amino acids composing at least the smaller protein molecules, and to map the three-dimensional configuration in which these units are arrayed. It is another matter entirely, however, to predict how amino acids will fold together to create the configuration.[4] Three-dimensional form is all-important in the case of enzymes, which are the protein catalysts, because it determines which substrate molecules the enzyme molecule captures and which reaction it then catalyzes. When procedures are worked out to predict the exact shapes that arise from particular amino acid sequences, the result is likely to be a revolution in biology and medicine. It will permit the design of artificial enzymes and other proteins with desirable properties in biochemical reactions—perhaps superior to those occurring naturally. The difficulty is technical rather than conceptual: Prediction requires the integration of binding forces among all the amino acids simultaneously, an enormous computational problem; and in order to proceed that far it must also measure the forces with a precision beyond the capability of present-day biochemistry.

Even greater challenges are presented by the conceptual reconstruction of cells and tissues from a knowledge of the constituent molecules and chemical processes obtained through reductive analysis. In 1994 the editors of *Science* asked a hundred cellular and developmental biologists to identify the most important unsolved problems in their field of research. Their responses focused prominently on the mechanisms of synthesis.[5] In rank order, the problems most often cited were the following: 1) the molecular mechanisms of tissue and organ development; 2) the connection between development and genetic evolution; 3) the steps by which cells become committed to a particular fate during development; 4) the role of cell-to-cell signaling in tissue development; 5) the self-assembly of tissue patterns during development of the early embryo; and 6) the manner in which nerve cells establish their specific connections to create the nerve cord and brain. Although these problems are formidably difficult, the researchers reported that considerable progress has already been achieved and that the solution of several may be reached within a few years.

To summarize to this point, the consilience of material cause-and-effect explanations is approaching continuity throughout the natural sciences, binding them together across the full span of space and time. Of the two complementary processes of consilience, reduction and synthesis, the more successful has been reduction, because it is both conceptually and technically easier to master. Synthesis good enough to be quantitatively predictive has progressed much more slowly, but it is now inching its way within biology to the level of cell and tissue.

Yet despite the progress of the natural sciences in understanding the natural world, they have remained sequestered from the other great branches of learning. The social sciences and humanities are generally thought to be too grounded in ineffable phenomena of mind and culture, too complex and holistic, and too dependent on historical circumstance to be consilient with the natural sciences.

That venerable perception, I believe, is about to change. The reason is that the natural sciences, doubling in information content every two decades or less, have now expanded to touch the material processes that generate mental and cultural phenomena. Two disciplines—the brain sciences and evolutionary biology—are now filling the ancient gap between dual epistemologies to serve as bridges between the great branches of learning.

The brain sciences are a conglomerate of research activities by neuroscientists, cognitive psychologists, and philosophers ("neurophilosophers") bound together by their conviction that the mind is the brain at work and, as such, can be understood entirely as a biological phenomenon. For their part, evolutionary biologists address the origin of the mental process, which is also considered a biological process. In particular, they focus on the instinct-like emotional responses and learning biases that affect individual development and the evolution of culture.

The key and largely unsolved problem of the brain sciences is the neuron circuitry and neurotransmitter fluxes composing conscious thought. The most important entrée to the problem is brain imaging, the monitoring of brain activity by the direct mapping of its metabolic patterns. The current method of choice in brain imaging is positron emission tomography (PET) scanning, which measures activity in different parts of the brain by the amount of their blood flow—hence the oxygen and energy being delivered to them. The patient is first injected with a small amount of rapidly decaying isotope of oxygen or another harmless radioactive material that emits elementary particles called positrons. The positrons interact with electrons in tissue reached by the isotope, resulting in radiation that can be picked up by a camera. As the patient experiences a sensation, or reflects upon a subject, or feels an emotion, blood flow increases within a tenth of a second in the activated part of his brain, and the corresponding change is detected by the scanner.

An alternative method of brain imaging is functional magnetic resonance imaging (fMRI). Its precursor recording method is static magnetic resonance imaging (MRI), which is based on the response of molecules in body tissues to radio waves after the molecules have been forced into a certain orientation by a powerful magnet. The magnitude of the response rises according to the water content of the tissues, which in turn increases while blood (half of which is water) flows into the active areas. Researchers convert MRI into fMRI, which enables them to use it to monitor brain activity, by recording multiple images through time. The images are then viewed in rapid succession to create moving images in the manner of conventional cinematography. The fMRI method is more efficient in this respect than PET scanning, having been improved to record hundreds of images per minute.

As in all biological research, the overall evolution of brain scanning is toward ever deeper, finer, and faster probes of activity. Other methods directed toward these goals, based on different physical phenomena from those employed in PET and fMRI, have recently opened a new chapter in imaging technology. One method, still limited currently to experimental use in animals, is the application of voltage-sensitive dyes to the surface of the living brain. The electrical conduction of the nerve fibers literally light up the dyes in patterns that can be tracked by photodiode cameras. Images have been recorded in excess of a thousand per second, allowing more nearly continuous monitoring than PET and fMRI scanning.

As the twenty-first century opens, we can expect to witness the invention of even more sophisticated methods of brain imaging, as well as refinement of those already in use. With luck, scientists will eventually reach their ultimate goal of monitoring the activity of intact brains continuously and at the level of individual nerve fibers. In short, the mind as brain-at-work can be made visible.

Brain imaging and experimental brain surgery, together with analyses of localized brain trauma and endocrine and neurotransmitter mediation, have permitted a breakout from age-old subjective conceptions of mental activity. Researchers now speak confidently of a coming solution to the brain-mind problem.

Some students of the subject, however (including a few of the brain scientists themselves), consider that forecast overly optimistic. In their view, technical progress has been largely correlative and has contributed little to a deeper understanding of the conscious mind. They consider it the equivalent of mapping the communicative networks of a city, correlating its activity with ongoing social events, and then declaring the material basis of culture solved. Even if brain activity is mapped completely, they ask, where does that leave consciousness, and especially subjective experience? How to express joy in a summer rainbow with neurobiology? Perhaps these phenomena rise from undiscovered physicochemical phenomena or exist at a level of organization still beyond our comprehension. Or maybe, as a cosmic principle, the conscious mind is just too complicated and subtle ever to understand itself.

This view of the mind as *mysterium tremendum* is, in the opinion of most brain researchers, unjustifiably defeatist. It is the residue of mind-body dualism, the impulse to posit a master integrator—whether corporeal or ethereal—located somewhere in the brain and charged with integrating information from the neural circuits and making decisions. The perception weighs too lightly the alternative and more parsimonious hypothesis: That activity of the neural circuits *is* the mind, and as a consequence nothing more of fundamental aspect is needed to account for mental phenomena at the highest levels. In this view, the hundred million or so neurons, each with an average of thousands of connections to other neurons, are enough to symbolize the thick stream of finely graded information and emotional coloring we introspectively recognize as composing the conscious mind.

To envision the immense amount of information that can be encoded, consider the following hypothetical example supplied by neurobiologists. Suppose that the chemoreceptive brain were programmed to sort and retrieve information by vector coding. Suppose further that combined activities of nerve cells imposing the codes classify individual tastes into combinations of sweetness, saltiness, and sourness. The brain need only distinguish 10 degrees in each of these taste dimensions to discriminate $10 \times 10 \times 10$ or 1,000 substances.

A large part, if not the totality, of mental activity comprises scenarios built with such symbolic information. The scenarios are usually reconstructions of the here and now, during which the brain is flooded with fresh sensory information. Many others recreate the past as it is summoned from long-term memory banks. Still others construct alternative possible futures, or pure fantasy.

According to the parsimonious theory of mind, emotions are the modifications of neural activity that animate and focus the scenarios. An act of decision is the prevalence of certain future scenarios over others; those that prevail are most likely to be the ones most conformable to instinct and reinforcement from prior experience. What we think of as meaning is the linkage among neural networks. Learning is the spreading activation that enlarges imagery and engages emotion. The self (to continue the parsimonious theory) is the key dramatic character of the scenarios. It must exist, because the brain is located within the body, and the body is the constant intense focus of real-time sensory experience and decision making.[6]

The primary environment in which the mind develops is culture. This highest level of human activity was defined in 1952 by Alfred Kroeber and Clyde Kluckhohn, out of a review of 164 prior definitions, as follows: "Culture is a product; is historical; includes ideas, patterns, and values; is relative; is learned; is based upon symbols; and is an abstraction from behavior and the products of behavior."[7] It comprises the life of a society, the totality of its religion, myths, art, technology, sports, and all the other systematic knowledge transmitted across generations.

Throughout this century scholars in all the branches of learning have treated culture as an entity apart, comprehensible only on its own terms and not those of the natural sciences. By this conception culture stands apart even if the mind has a reducible, material basis; it must do so first because the fine details of the cultures of individual societies are historically determined, and second because cultures comprise phenomena too complicated, too flickering through time, and too subtle to be subject to natural scientific analysis.

A fixed belief in the independent nature of culture has contributed to the isolation of the social sciences and humanities from the natural sciences throughout modern history. It is the basis of the discontinuity famously cited by C. P. Snow in 1959 as separating the scientific culture from the literary culture. Now there is reason to believe that the difference is not a true epistemological discontinuity, not a divide between two kinds of reality, but something far less forbidding and yet much more interesting. The boundary between the two cultures is instead a vast, unexplored terrain of phenomena awaiting entry from both sides.

The terrain is the interaction between genetic evolution and cultural evolution. We know that culture is learned. At the same time, evidence is mounting that learning is genetically biased; it is becoming increasingly accepted that culture is influenced by human nature. But what exactly is human nature? It is not the genes, which prescribe it, or the cultural universals, which are its most obvious products. It is the epigenetic rules, the hereditary biases that guide the development of individual behavior. There are several examples of epigenetic rules that can be cited in this early stage of investigation.

The facial expressions denoting the elementary emotions of fear, loathing, anger, surprise, and happiness are human universals and evidently inherited. They are adjusted by cultural evolution within individual societies to project particular nuances of meaning. The smile, one of the basic elements of emotive communication, appears at two to four months in infants everywhere, virtually independent of environment. It occurs on schedule in deaf-blind infants and even in thalidomide-crippled children who cannot touch their own faces.[8] The tendency to fear snakes is another human universal. It is furthermore widespread, if not universal, in all other Old World primate species. Snakes are among the few stimuli that easily evoke true phobias in people—the deep and intractable visceral reactions acquired with only one or two frightening experiences. They share their power with heights, closed spaces, running water, spiders, and other ancient perils of humanity; a similar degree of sensitivity does not exist for knives, guns, electric sockets, automobiles, and other modern sources of risk. The cultural consequences of the response to snakes, combining fear and intense curiosity, are manifold. Snakes are among the animals most commonly experienced in dreams, even among urbanites who have never seen one in life. They play prominent mythic roles in cultures around the world, taking new forms variously as demons, dragons, seducers, magical healers, and gods.[9]

Automatic incest avoidance is universal in primate species studied to date, including *Homo sapiens*. The generally accepted adaptive explanation is the heightened risk that inbreeding poses of producing defective offspring, and that evolutionary inference is well supported by the evidence. The closer the genetic relationship of parents, the more likely they will bring together matching recessive genes that are deleterious in a double dose. Children of full siblings and of fathers and daughters, for example, have twice the early mortality rate of outbred children. Among those that survive, ten times more suffer genetic defects such as heart deformities, deaf-mutism, mental retardation, and dwarfism. The epigenetic rules, or hereditary developmental biases that prevent incest, are two-layered in apes, monkeys, and other non-human primates. First, all species so far studied for the trait (nineteen worldwide) practice the equivalent of human exogamy: Young individuals leave the parent group and join another before they attain full maturity. Second, all species examined for the possible existence of the Westermarck effect also display that phenomenon. This means that individuals are sexually desensitized to individuals with whom they have been closely associated while very young, normally their parents and siblings. The critical period for the effect in human beings is the first thirty months of life. Out of the Westermarck effect have apparently risen incest taboos with all their supporting arsenal of legends and myths. The effect is enhanced in some but not all societies by a third barrier: the direct observation and correct rational understanding of the ill effects of incest.[10]

Similar examples of epigenetic rules have multiplied in the literature of biology and the behavioral sciences during the past several decades. They have been found in virtually all categories of human behavior, including sexual and parental bonding, the acquisition of language, and even the cardinal role of trust during contract formation. They leave little doubt that a true hereditary human nature exists, and that it includes social behaviors held in common with nonhuman primate species and others that are diagnostically human.

Such is the interdisciplinary subject awaiting study by all the great branches of learning, and I can think of no more important intellectual undertaking. The relation between biological evolution and cultural evolution is, in my opinion, both the central problem of the social sciences and humanities and one of the great remaining problems of the natural sciences.

The process by which genetic evolution and cultural evolution appear to be linked is usually called gene-culture coevolution. The theory of gene-culture coevolution incorporates the two levels of approach I cited earlier as the core of modern biology.[11] Put as briefly as possible, they are that living processes are physicochemical and also self-assembled by natural selection. The first level is composed of proximate explanations, which describe the structures and processes by which an organism responds. The question of interest in any proximate explanation is, How does the phenomenon occur? The second level is composed of ultimate, or evolutionary, explanations, which account for the origin of the structures and processes, usually by the adaptive advantage they confer on organisms. The question of interest at this level is, *Why* does the phenomenon occur? In the case of hereditarily based incest avoidance, the proximate causes are emigration and the Westermarck effect. The ultimate cause is the deleterious effects of inbreeding, which by natural selection has driven the species toward emigration and the Westermarck effect.

The theory of gene-culture coevolution is still spotty and largely untested. Nevertheless, I believe that most researchers on the subject would agree with the following outline of the present form of the theory: People survive and leave offspring to the degree that they learn and adapt to the culture of their society, and the societies themselves flourish or decline in proportion to the effectiveness of their adaptation to their environment and surrounding societies. For hundreds of millennia certain aptitudes and cultural norms have arisen that are consistently adaptive in this Darwinian sense. They include language facility, cooperativeness within the group, exogamy and incest avoidance, rites of passage, territoriality, male polygyny, and parent-offspring bonding. Hereditary epigenetic rules have evolved that pull individual preference, and hence cultural evolution, toward these norms. They comprise the elements of what we subjectively call human nature. The genes prescribing them also increase in frequency as a result of the same process. Spreading through the population, maintained by the edge they give most of the time in survival and reproduction, they have secured the stability of human nature across societies and generations.

To conclude my synopsis of the theory, cultural evolution is much faster than genetic evolution. One result is nongenetic cultural diversity, which scatters particular cultural variants around each central, genetic trend to a degree determined by the strength of the epigenetic rules affecting them. The products of cultural evolution, multiplying rapidly through the population, can improve the fitness of individuals and societies, or they can reduce them. But only if the advantage or disadvantage is sustained for many generations—population genetics theory would suggest at least ten—can the epigenetic rules and the genes prescribing them be replaced. That is why human nature today remains Paleolithic even in the midst of accelerating technological advance. Thus corporate CEOs impelled by stone-age emotions work international deals with cellular telephones at thirty thousand feet.

If it is granted that the human condition is subject to consilient explanation from genes to mind to culture, even as a working hypothesis, the consequences to follow will be considerable. The first is support across the great branches of learning for what can appropriately be called "gap analysis" as a research strategy.[12] Already a mainstay of the natural sciences, gap analysis is the systematic attempt to identify domains of phenomena in which important discoveries are most likely to be made. Its most productive method is reduction, the search for novel phenomena, or at least the search for novel explanations of phenomena already known, by examination of the next level of organization down. Successful reduction confirms the existence of elements in the lower level that interact to create the higher level. In this manner, molecular biology was created de novo from the basic chemistry of macromolecules, and the study of cells and tissues was revolutionized by molecular biology.

The social sciences, I believe, will advance more rapidly if they adopt a consilient worldview and the gap analysis suggested by it leading to reductionist analysis. They have failed to give this approach a try, except in a few sectors such as biological anthropology, largely because of their aversion to biology. The reasons for the aversion are complex, stemming partly from the effort of the social science disciplines—anthropology, economics, political science, and sociology—to maintain intellectual independence, partly from the daunting complexity of the subject, and partly from fear of the misuse of biology to support racist ideology.

Still, biology is the logical foundational discipline of the social sciences. I mean by this assessment biology as broadly defined, including much of contemporary psychology, especially cognitive psychology, which is in the process of being subsumed by neurobiology and the brain sciences. A great majority of social scientists, including the most influential theoreticians in economics, build their models as if this information does not exist. Their conceptions of human behavior come either from folk psychology—intuitive notions that seem right but are often factually wrong—or from notions of the mind as an optimizing device for rational choice. They ignore contrary signs from genetics, neurobiology, cognitive psychology, and the many quirky properties of human nature. For them history began a few thousand years ago with the rise of complex societies, overlooking the fact that it began hundreds of thousands of years ago with the evolutionary origins of human nature in hunter-gatherer bands.

In summary, it is hard to imagine how the social sciences can unite and achieve general, predictive theory without taking a reductionist approach to the phenomena of human nature, both their proximate causes in the machinery of the brain and their ultimate causes in deep, evolutionary history.

The theory and criticism of the arts can also benefit in the same fashion. Let me cite several examples already in hand. We now know, from neurobiology and the brain sciences, how the brain breaks down and classifies the continuously varying wavelength of visible light into four basic colors, namely, blue, green, yellow, and red. The process has been tracked in segments from the base sequences in the DNA that prescribe the cone pigments of the photosensitive retinal cells to the nerve-cell sequences that lead from the retina to the primary visual cortex at the extreme rear of the brain. From anthropological and linguistic studies we know that people in societies around the world fix their color terms toward the centers of the primary colors in the spectrum and away from the intermediate and hence ambiguous wavelengths. Finally, we know that as societies increase their color vocabularies, in the course of cultural evolution, they tend to employ up to eleven basic terms, usually accumulating them in the following sequence: Languages with only two basic color terms use them to distinguish black and white; languages with only three terms identify black, white, and red; languages with only four terms have words for black, white, red, and either green or yellow; languages with only five terms have words for black, white, red, green, *and* yellow; and so on until all eleven terms are included, as exemplified in the English language. The sequence cannot be due to chance alone. If the terms were combined at random, there would be 2,036 possible combinations. But for the most part they are drawn from only 22. Surely this is the kind of information needed to produce a coherent theory of aesthetics in the visual arts.[13]

In another domain relevant to visual aesthetics, neurobiological measurements have shown that the brain is most aroused by abstract designs in which there is about 20 percent repetition of elements. That is the amount of redundancy found in a simple maze, two turns of a logarithmic spiral, or an asymmetrical cross. It seems hardly a coincidence that roughly the same property is shared by a great deal of the art in friezes, grillwork, colophons, and flag designs. Or that it crops up again in the glyphs of ancient Egypt and Mesoamerica as well as the pictographs of Japanese, Chinese, Thai, Bengali, and other Asian languages. The response appears to be innate: Newborn infants gaze longest at figures with about the same amount of redundancy.[14]

In yet another topic of aesthetics, ideal female facial beauty as judged in at least two cultures, European and Japanese, has recently been found to follow some surprising principles. Using blended and artificially altered photographs, psychologists have discovered that the most admired facial features are near the anatomical average of the population but with heightened cheekbones, reduced chin size, enlarged eyes, and shortened distance between the nose and chin.[15] The cause of this effect, if upheld as inborn by further cross-cultural and developmental studies, is unknown. It could represent an innate recognition of the signs of youthfulness and hence greater reproductive potential.

The creative arts themselves, in literature, the visual arts, drama, music, and dance, may not be affected significantly by such knowledge from the natural sciences. The purpose of the arts is to transmit personal experience and emotion directly from mind to mind while avoiding explanation of the logic behind the creative work; thus, *ars est celare artem*, it is art to conceal art. But theory and criticism of the arts, which does attempt this mode of explanation, cannot help but be strengthened by the new information. If the greatest art is indeed that which touches all humanity, as commonly said, it follows that consilient cause-and-effect accounts of human nature will become increasingly foundational to sound theory and criticism.

ENDNOTES

[1]This essay presents in much abbreviated form some of the arguments in my book-length exposition of the same general subject, *Consilience: The Unity of Knowledge* (New York: Knopf, 1998).

[2]The Ionian enchantment is discussed by Gerald Holton in *Einstein, History, and Other Passions* (Woodbury, N.Y.: American Institute of Physics Press, 1995).

[3]*The Shorter Science and Civilisation in China: An Abridgment of Joseph Needham's Original Text*, Vol. I, prepared by Colin A. Ronan (New York: Cambridge University Press, 1978).

[4]In characterizing the prediction of three-dimensional protein structure, I benefited greatly from an unpublished paper presented by S. J. Singer at the American Academy of Arts and Sciences in December 1993; he has also kindly reviewed my account.

[5]On the opinions of cell and developmental biologists concerning the frontiers of their field, see "Looking to Development's Future," by Marcia Barinaga, *Science* 266 (1994): 561–564.

[6]Among the many recent works I have used to interpret the consensus of students of the mind-body problem are Patricia S. Churchland, *Neurophilosophy: Toward a Unified Science of the Mind-Brain* (Cambridge, Mass.: MIT Press, 1986); Paul M. Churchland, *The Engine of Reason, the Seat of the Soul* (Cambridge, Mass.: MIT Press, 1995); Antonio R. Damasio, *Descartes' Error: Emotion, Reason, and the Human Brain* (New York: G. P. Putnam, 1994); Daniel C. Dennett, *Consciousness Explained* (Boston: Little, Brown, 1991); J. Allan Hobson, *The Chemistry of Conscious States: How the Brain Changes Its Mind* (Boston: Little, Brown, 1994); and Stephen M. Kosslyn and Oliver Koenig, *Wet Mind: The New Cognitive Neuroscience* (New York: Free Press, 1992).

[7]Alfred Kroeber and Clyde K. M. Kluckhohn, "Culture: A Critical Review of Concepts and Definitions," *Papers of the Peabody Museum of American Archaeology and Ethnology, Harvard University*, vol. 47 (1952), no. 12, 643–644.

[8]On basic facial expressions: the literature, including smiling, is reviewed by Charles J. Lumsden and Edward O. Wilson in *Genes, Mind, and Culture* (Cambridge, Mass.: Harvard University Press, 1981) and by the pioneer behavioral biologist Irenäus Eibl-Eibesfeldt in *Human Ethology* (Hawthorne, N.Y.: Aldine de Gruyter, 1989).

[9]On the fear of snakes and the origin of the serpent myth: Balaji Mundkur, *The Cult of the Serpent: An Interdisciplinary Survey of Its Manifestations and Origins* (Albany, N.Y.: State University of New York Press, 1983) and Edward O. Wilson, *Biophilia* (Cambridge, Mass.: Harvard University Press, 1984).

[10]On incest and its avoidance in human beings and other primates: Arthur P. Wolf, *Sexual Attraction and Childhood Association: A Chinese Brief for Ed-*

ward Westermarck (Stanford, Calif.: Stanford University Press, 1995) and William H. Durham, *Coevolution: Genes, Culture, and Human Diversity* (Stanford, Calif.: Stanford University Press, 1991).

[11]The expression gene-culture coevolution and a first general theory pertaining to it, in the sense of combining models from genetics, psychology, and anthropology, were provided by Lumsden and Wilson in *Genes, Mind, and Culture*. A review and update of the subject are given in my more general book *Consilience*.

[12]"Gap analysis" is a term I have borrowed from conservation biology. It means the method of mapping known ranges of threatened plant and animal species and using the information to select the best sites to set aside as reserves. See J. Michael Scott and Blair Csuti, "Gap Analysis for Biodiversity Surveys and Maintenance," in Marjorie L. Reaka-Kudla et al., eds., *Biodiversity II: Understanding and Protecting Our Biological Resources* (Washington, D.C.: Joseph Henry Press, 1997), 321–340.

[13]A full account of the biological and cultural origins of color perception and vocabulary is given by multiple authors in Trevor Lamb and Janine Bourriau, eds., *Colour: Art & Science* (New York: Cambridge University Press, 1995).

[14]On the optimum amount of redundancy in design: see the review by Charles J. Lumsden and Edward O. Wilson, *Promethean Fire* (Cambridge, Mass.: Harvard University Press, 1983).

[15]On female facial beauty: "Facial Shape and Judgements of Female Attractiveness," by D. I. Perrett et al., *Nature* 368 (1994): 239–242. Other aspects of ideal physical characteristics are discussed by David M. Buss in *The Evolution of Desire* (New York: BasicBooks, 1994).