The Three Cultures

NATURAL SCIENCES, SOCIAL SCIENCES, AND THE HUMANITIES IN THE 21ST CENTURY

Jerome Kagan
Harvard University

CAMBRIDGE
UNIVERSITY PRESS

Contents

1

Characterizing the Three Cultures

The influential British novelist and science administrator C. P. Snow, who had trained as a natural scientist, published a lecture delivered in Cambridge University in 1959 titled "The Two Cultures." The lecture and the fifty-one-page book that followed provoked heated discussion because of its brash dismissal of the humanities as an intellectual mission lacking in rigor and unable to contribute to the welfare of those living in economically underdeveloped regions. Not surprisingly, humanists resented Snow's allegations that world peace and prosperity would profit from training more scientists and engineers and fewer historians, philosophers, and literary critics. Three years later, F. R. Leavis, an admired literary critic at Cambridge University, delivered an unusually harsh, occasionally impolite, rebuttal that caricatured Snow as a failed chemist, incompetent novelist, and social commentator who was ignorant of the world's serious problems.

Snow composed his essay as America was about to experience an extraordinary expansion in higher education that led to a fourfold increase in faculty (from 250,000 to more than 1 million) and a sevenfold increase in students to a total of 15 million, compared with only 50,00 Americans who were attending colleges in 1870.[1] These changes were due primarily to the establishment of new community colleges and rising enrollments in state universities trying to accommodate the many World War II veterans who, assisted by the government's decision to subsidize their education in gratitude for their service, chose to attend college rather than return to the working-class jobs held by their fathers.

There was a proportionate swelling in the funds available for research and in the numbers of scientists, research administrators, practitioners, journalists, and teachers managing, utilizing, disseminating, or teaching the products of science. More than 5 million scientific papers were published worldwide from 1992 to 2002, and 40 percent of that very large number were written by American investigators.[2] Most youths who choose a life in science in 2009 do not appreciate that the term *scientist* (as distinct from a physician or philosopher), as well as the opportunity to pursue a research career independent of one's social class or ethnicity, are less than 170 years old. These facts, combined with a public that had become more skeptical of select scientific claims and the idealistic depiction of scientists as pure of motive in their pursuit of truth, invite a re-examination of Snow's bold thesis.

Although the primary concerns, sources of evidence, and concepts remain the most important nodes of difference among natural scientists (physicists, chemists, and biologists), social scientists, and humanists, the three communities vary on six additional dimensions less pertinent to their epistemologies. (I consider the investigators who study the biological bases for, or evolutionary contributions to, animal or human behavior as natural scientists.) The nine dimensions follow:

1. The primary questions asked, including the degree to which prediction, explanation, or description of a phenomenon is the major product of inquiry
2. The sources of evidence on which inferences are based and the degree of control over the conditions in which the evidence is gathered
3. The vocabulary used to present observations, concepts, and conclusions, including the balance between continuous

properties and categories and the degree to which a functional relation was presumed to generalize across settings or was restricted to the context of observation

4. The degree to which social conditions, produced by historical events, influence the questions asked
5. The degree to which ethical values penetrate the questions asked and the conclusions inferred or deduced
6. The degree of dependence on external financial support from government or industry
7. The probability that the scholar works alone, with one or two others, or as a member of a large team
8. The contribution to the national economy
9. The criteria members of each group use when they judge a body of work as elegant or beautiful

Most intellectual efforts consist of three components: (1) a set of unquestioned premises that create preferences for particular questions and equally particular answers, (2) a favored collection of analytical tools for gathering evidence, and (3) a preferred set of concepts that are the core of explanations. A naïve observer who held no premises about the nature of solid objects might conclude that the bottom half of a pencil resting in a half-filled glass of water had been bent by the liquid. Social scientists and humanists share more premises, analytic tools, and concepts, as well as more of the other criteria in Table 1, than each does with natural scientists. Natural scientists emphasize material processes, minimize the influences of historical and cultural contexts and their associated ethical values, and are primarily concerned with the relations between a concept and a set of observations. Social scientists and humanists resist awarding biology too much influence, rely heavily on semantic networks and, therefore, are often as concerned with the relations among a set of semantic terms as they are with the relation between a concept and evidence, and frequently seek answers that affirm or disconfirm an

TABLE 1. *Comparison of the three cultures on nine dimensions*

Dimension	Natural Scientists	Social Scientists	Humanists
1. Primary interests	Prediction and explanation of all natural phenomena	Prediction and explanation of human behaviors and psychological states	An understanding of human reactions to events and the meanings humans impose on experience as a function of culture, historical era, and life history
2. Primary sources of evidence and control of conditions	Experimentally controlled observations of material entities	Behaviors, verbal statements, and less often biological measures, gathered under conditions in which the contexts cannot always be controlled	Written texts and human behaviors gathered under conditions of minimal control
3. Primary vocabulary	Semantic and mathematical concepts whose referents are the material entities of physics, chemistry, and biology, and assumed to transcend particular settings	Constructs referring to psychological features, states, and behaviors of individuals or groups, with an acceptance of the constraints that the context of observation imposes on generality	Concepts referring to human behavior, and the events that provoke them with serious contextual restrictions on inferences
4. The influence of historical conditions	Minimal	Modest	Serious

Dimension	Natural Scientists	Social Scientists	Humanists
5. Ethical influence	Minimal	Major	Major
6. Dependence on outside support	Highly dependent	Moderately dependent	Relatively independent
7. Work conditions	Both small and large collaborations	Small collaborations and solitary	Solitary
8. Contribution to the national economy	Major	Modest	Minimal
9. Criteria for beauty	Conclusions that involve the most fundamental material components in nature inferred from evidence produced by machines and amenable to mathematical descriptions.	Conclusions that support a broad theoretical view of human behavior.	Semantically coherent arguments described in elegant prose.

implicit ethical ideal. However, the meanings of the concepts used by the three groups deserve special attention because the communities use different sources of evidence.

THREE VOCABULARIES

The meaning of a sentence, for speakers and listeners, is based on the actual events that are named, as well as the network of ideas that was the origin of the statement. The meaning of the declaration, "The bulls were beaten yesterday" depends on whether the referents for bulls were animals or the Chicago basketball team. The three cultures represent language communities that impose distinct meaning networks on their important concepts and, like the dispersed Indian groups of fifth century Meso-America, compete with each other for dominance. One of the insights of the twentieth century, due in large measure to Ludwig Wittgenstein, is that the meanings of most statements are not transparent. Application of this idea to a scientific proposition implies that meaning depends on the specific observations to which a statement refers, and, therefore, the procedure that generated the evidence and the web of meanings that define a theory.

The vocabularies of each culture contain a number of concepts with technical definitions that are of primary interest to only one group (e.g., gluon and transposon for natural scientists, attribution error and gross domestic product for social scientists, and antinomy and historical era for humanists). The vocabulary of psychoanalysts attributed a unique meaning to *energy* that was neither the one implied by the Chinese concept *ch'i*, nor the meaning physicists understood in the principles of thermodynamics. But the three cultures also use terms with exactly the same sound and spelling that have different meanings for each culture, even though the scholars may not recognize that fact. The terms *fear*, *capacity*, *arousal*, *memory*, and *count* are examples. The meaning of "fear" in T. S. Eliot's line: "I'll show you fear in a handful of dust" is not the meaning intended by the social scientist who writes that "The heritability of realistic fears is less than the heritability of unrealistic fears," nor the meaning understood by the biological scientist who states that "Rats that stop moving when they hear a tone that had predicted electric shock are in a state of fear."

Even though the poet, psychologist, and biologist use the same word, each is naming a distinctly different phenomenon. Eliot was naming the subjective feeling that pierced consciousness when he reflected on the value confusion and spiritual emptiness that permeated Europe after World War I. The psychologist was referring to the answers of adults filling out questionnaires asking them about their sources of worry. The biologist was describing a rat's immobility in response to a conditioned stimulus that had signaled an unpleasant event in the past. Eliot could have used the word *angst*; the psychologist could have used the word *worry*, and the neuroscientist could have used the term *vigilant*.

The descriptions of a hypothetical person called Max make this point clearly. Natural scientists would use a vocabulary that referred to features like bone density, glucose level, blood flow, and electrical currents in body and brain. Social scientists would describe Max's identifications with his family, gender, ethnicity, and nation; the shame he feels as an American over the deaths of innocent Iraqi citizens; and childhood memories of family holidays at the seashore. Humanists would refer to his membership in a family that migrated from Ireland to America in the nineteenth century, his nostalgia for summer when the November trees are bare, and the blend of powerlessness and melancholy that pierces consciousness when he reflects simultaneously on his aging father and Dylan Thomas's line, "Do not go gently into that good night." None of these three descriptions can be translated into one of the others without losing some meaning.

The first cohort of economists treated the physicists' meaning of *capacity* in the sentence, "Energy is the capacity to do work" as similar to its meaning in "Money is the capacity to purchase goods." As a result, they assumed that the equations of thermodynamics might be appropriate in mathematical models of the economy. They failed to appreciate that many predicates assume different meanings when they are joined to different nouns because the validity of every declaration rests with a full sentence rather than with a single word. The predicate *fall*, for example, has four distinct meanings in each of the four expressions: "Temperatures fall," "Prices fall," "Apples fall," and "Spirits fall."

Even some terms in the vocabulary of natural scientists have different meanings. The meanings of mass, space, and time in Newton's equations are not synonymous with the meanings that Einstein understood. Nonetheless, Newton's concepts work well for an apple falling from a tree and Einstein's terms explain the energy emitted from a fissionable uranium atom. Acceptance of relativity theory and quantum mechanics during the last century, which altered the traditional meanings of time, space, and objects, allowed both philosophers and scientists to appreciate that the meaning and validity of every proposition are restricted to the language system to which it belongs, and might not be valid in another system.

A tolerance toward multiple meanings for words belonging to distinct language systems allows us to believe, simultaneously, that physicists writing in the mathematical language of quantum mechanics are correct when they declare that there are no stable objects in the world, and psychologists are correct when they state that the world consists of solid objects like cups, that can be touched, moved, and filled with liquid. We accept both statements as true without the disturbing feeling of cognitive dissonance that accompanies logically contradictory ideas because they belong to separate language systems. This principle allows neuroscientists to use the word *fear* to describe a pattern of neuronal activity and psychologists to use the same word to describe a person's judgment of his or her subjective experience, even though the term *fear* has different meanings in these two language networks.[3] Unfortunately, many scientists experience more cognitive dissonance in this instance than they do in the case of the reality of cups.

The evidence gathered by biologists and psychologists awards different meanings to the term *aroused*. Most adults report that the color red induces a feeling of arousal or excitement, whereas blue reduces the intensity of subjective arousal. However, the brain wave profiles that are indicative of enhanced arousal of cortical neurons occur to blue rather than red. Thus, neuroscientists should not equate the arousal that is defined by a pattern of cortical activity with the psychological experience of arousal.[4]

This same argument applies to *memory*. A group of Chinese adults who had been exposed to Chinese during early childhood, but had consciously forgotten their first language after learning English as a second language, indicated whether the second word in a sequence of two English words was or was not semantically related to the first; for example, dog and cat are related but dog and crayon are not. The neurons of the temporal lobe generate a distinctive wave form in the electroencephalogram when a second word is semantically unrelated to the first about three-tenths of a second before consciousness recognizes that the second term is incongruent.[5]

The bilingual Chinese who were convinced that they lost their childhood knowledge of Chinese showed a smaller than expected wave form when a second word was unrelated to the first in English, but happened to share a Chinese character. The English words *train* and *ham* are unrelated, but share the Chinese character *huo*. Thus, when the word *ham* appeared after *train*, the bilingual Chinese person showed a smaller wave form to ham than did monolingual English speakers, even though they were totally unaware of the fact that their brains had responded to a shared meaning that was unavailable to their consciousness.[6] This fact implies that their brains had preserved some feature of the meanings of the Chinese characters and, therefore, the terms *memory* and *remember* have different meanings when a brain response or conscious detection of meaning supplies the evidence. Psychologists invented the concept of implicit memory to account for this fact.

The term *count* provides a third example of the conceptual confusion that occurs when neuroscientists use brain profiles to define a concept that is essentially psychological. Although this term was invented originally to represent the ability to arrange the cardinal numbers in an ordinal sequence, two neuroscientists concluded that brains can *count* because the profiles of activation were different for displays of 20 compared with 30 dark circles.[7] However, the brain was responding to the perceptual difference in the spatial distribution of distinctly contoured elements and not to their number. A person gazing at a shelf containing eighteen books sees an array of objects varying in height, width, and color, not eighteen objects. Infants see the protuberances on their hands; it will be several years before they learn that each hand has five fingers. The blood flow patterns that are normally activated when people are counting were dissimilar to two displays of three objects in different spatial arrangements (one array grouped two of the objects close together and the other did not). If the neurons in this area were counting, the blood flow patterns should have been the same because both arrays had exactly the same number of objects.[8] Moreover, the areas that are active when people are looking at arrays of discrete objects are different from the areas that are active when people are reading numbers.[9] The brain would respond differently to clocks set at 6:00 and 3:00 o'clock, but that does not mean that the activated neurons were responding to the concept of time. Number and time are acquired concepts imposed on experiences, and appreciation of their meanings relies on circuits involving distinct brain sites.

Most living forms, including algae, display a regular twenty-four- to twenty-five-hour cycle of metabolic activity, but biologists do not suggest that algae are "counting" the passing minutes of each day. Neither are foraging bees, whose dance on returning from a bed of flowers to their hive varies as a function of distance between the hive and the flowers, counting the meters between the two places. It turns out that their nervous system is registering the amount of contour they fly over on their visit to the flowers and the accompanying variation in neural activity determines the quality of the dance.[10] Bees also scatter the pollen of the plants they visit, but that fact does not mean that they are altruistic or "good Samaritans." The hair cells on the basilar membrane of the inner ear respond differentially to sounds of varying frequencies, because of the inherent variation in their structure, but these tiny sensory receptors are not "counting" the frequencies in the incoming stimulation. The ability of neuronal clusters to react differentially to varied numbers of objects within the first one-fifth of a second is an intriguing phenomenon worthy of study, but this fact does not mean that neurons or brains are "counting." The neurons of the primary auditory cortex of the ferret respond as humans do to sounds that represent varied English phonemes, but it would be a semantic error to say that the ferret is responding to the components of human speech.[11]

A study of brain development in a large, representative sample of American children and adolescents from many cities and varied social class backgrounds reveals the stubborn fact that the meaning and validity of an inference referring to a psychological state always depend on the source of evidence. The scientists gathered information on changes in the human brain across more than a decade of development. One surprising finding was the absence of dramatic differences in patterns of brain growth among children who were members of families from divergent social classes.[12] This observation is puzzling because social class is, far and away, the best predictor of a child's IQ score, vocabulary, grades in school, the probability of mental illness, gang membership, violent aggression, and a criminal record in every society that has been studied.[13] If investigators had to predict the vocabulary, academic achievements, number of arrests for criminal activity, and number of bouts of depression in 500 adults, and could choose either the educational level and vocation of their family of rearing or measurements of their brain, those who selected the person's social class would be more accurate.[14]

THE CASCADE OF EVENTS

The critical point is that the vocabulary biologists use to describe the brain's properties does not, at least at present, correspond closely in meaning to the vocabularies used by social scientists and humanists.

The latter two disciplines describe the late phases of a cascade that begins in a series of brief neuronal events and ends in a perception, thought, feeling, or behavior that lasts for a longer time.[15] That is, an intention to get up and go to the refrigerator to find food lasts much longer than any of the brain states that occur during the time that transpired between the original idea and opening the refrigerator.

Different metrics apply to the phases of a cascade that began with the response of a single neuron and proceeded to the activity of a cluster of neurons, a circuit, a network of circuits, and, finally, to a psychological outcome. The activity of a single neuron is usually measured in terms of the frequency of spike potentials (i.e., firing of the cell). The metric for a cluster of neurons is usually the number or proportion firing at the same frequency. The metric for a circuit is usually coherence (meaning the correspondence between the frequency spectra at two different sites), and the metric for a network of circuits is the probability of co-activation. The metrics for psychological outcomes include the frequency, speed, or accuracy of a response; the duration of a perception, emotion, or thought; the clarity of a representation; and the valence and intensity of a feeling. These metrics cannot be translated into any of the preceding ones.

A documented illustration of this principle involves the unexpected discovery that young rat pups separated from their mothers for a brief interval become adults that cope with certain stressors better than those that did not experience the separation. At least three phases intervene between the separation and the adult behavior. The first phase refers to the consequences of the fact that rat mothers are likely to lick and groom a separated infant, whose skin is cooler, with more vigor than they display with a pup that was not separated. The more vigorous licking affects the pup's genome by preventing the methylation of a specific nucleotide in the promoter region of the gene responsible for a class of receptors in the hippocampus that is activated by the hypothalamic–pituitary–adrenal axis (HPA axis). Because methylation usually leads to less efficient expression of the gene, the gene in the licked infants is more fully expressed than in the pups that were licked less vigorously. The phenomena of this initial phase are described with terms referring to the four nucleotides that comprise DNA, the process of methylating one of them, and the degree of expression of that gene. The words for the second phase refer to the protein receptors located on select neurons in the hippocampus. The possession of a dense set of receptors means that there will be feedback to the neurons of the HPA axis that results in a dampening of HPA activity and, therefore, modulation in the secretion of the molecules that lead to behavioral signs of a state of stress. The words for this third phase refer to feedback mechanisms, the molecule corticosterone, and states of stress. Thus, we need three distinct vocabularies to explain why a separated rat pup becomes an adult that is less avoidant and less "fearful" of challenge and novel environments. (It is intriguing to wonder whether there might be a comparable process in human infants; for example, do human mothers who caress their infants a great deal provoke an analogous phenomenon in the brains of their children?) The important point is that the vocabulary that describes each of the phases in any cascade that begins with a genetic or brain event and ends with a behavior has some degree of autonomy.

Even a behavior as serious as an adolescent's suicide is influenced, at least in America, by the individual's social class (more common among the poor), region of the country (more common in less densely populated areas in the western states), time of year (more prevalent in spring and summer), and day of the week (suicides are most common on Monday).[16] Thus, neuroscientists do not add much clarity to the psychological concept of *self* when they suggest that it is a pattern of coherence in neural activity.[17] One cannot see a forest while inside it. One cannot understand the psychological state of a depressed person who describes her inner world as dark, devoid of energy, and hungering for a silence that is free of the noise of crowds by remaining within a vocabulary that refers only to biological processes.

The critical point in this discussion is that the concepts in the social sciences and the humanities refer to emergent phenomena that cannot be described with the vocabulary used by natural scientists. The timbre of a violin sonata cannot be translated into the physicist's terms for frequency, intensity, and time; the balance in a Monet painting cannot be translated into sentences referring to color, contour, or shape; and, as noted, the meaning psychologists attribute to the terms *remember*, *count*, or *fear* cannot be replaced with statements referring only to brain states or structures. Put simply, the phenomena that humanists and social scientists describe represent special combinations of events that require their own vocabulary. Physicists confront a similar problem. The world of quantum processes is probabilistic and discontinuous, whereas the masses of several stones and their accelerations when struck with a known force are certain and continuous. There is a fuzzy boundary between these two worlds, which require different vocabularies, and physicists do not yet understand how objects and their functions emerge from a quantum world. Neuroscientists do not yet understand how perceptions, thoughts, feelings, and actions emerge from the activity of neurons.

An explanation is satisfying when investigators can imagine what is happening at each transition in a cascade and cannot think of another way to account for the transitions.[18] An understanding of the relations between phases has been most successful when scientists concentrated on contiguous phases (e.g., the relation between genes and neurochemistry or between brain chemistry and moods), and less successful when they skipped phases and tried to understand the relations between genes and particular moods because variations in life history influence the emotional profiles of individuals with the same gene.

Biological and social scientists focus on different phases, or halfway houses, in the complete cascade that defines an observed phenomenon. Therefore, the three cultures think about the same event in different ways. Their perspectives are analogous to the incompatible perceptions of a drawing that can represent either a young or old woman as a function of where viewers focus their attention. Each perspective has consistency and coherence within each of the language communities, but not always across communities. This suggestion would not bother mathematicians, who understand that a mathematical idea, like infinity, can assume different meanings in different mathematical arguments. Similarly, the meaning of *population density* in the United States depends on whether one computes the ratio of the total population to the total geographical area or the ratio of the number of individuals living in areas where most Americans live over that more restricted area. The first estimate of 70 people per square mile implies a low population density; the second ratio of 3,000 per square mile evokes a different image.[19]

TROPES

There is one more reason for the ambiguity that surrounds the meanings of words. Humans have an automatic tendency to relate two or more networks for different concepts and detecting, with minimal effort, a single semantic node that is shared between or among them. When the shared node awards a nonliteral meaning to the concept, as in the metaphor "humans are gorillas," it is called a trope. The features of concepts vary in their essentialness or defining property. For example, the ability to fly is a defining property of birds, whereas the ability to catch fish is a secondary property. Most tropes, or metaphors, are satisfying when a defining property of the second term is a secondary property of the first term. Hence, the metaphor "Humans are gorillas" is acceptable because the capacity for aggression is a primary feature of gorillas but a secondary feature of humans. Hence, the statement "Gorillas are humans" is not a satisfying metaphor. Tropes can be categorized as satisfying or unsatisfying, coherent or incoherent, but cannot be evaluated as true or false. Only novelists and poets are permitted to describe April as cruel or jealousy as the green emotion. Most Americans have acquired the semantic nodes helpless, weak, and uncontrolled as defining features for the network *baby*. Hence, an American adult who was called a baby is likely to feel insulted because the features helpless, weak, and uncontrolled are inconsistent with the nodes representing the literal understanding of *adult*. The node for *beast* is primary in the Japanese network for *monkey*, but not in the network possessed by most Americans.[20] Thus, a Japanese person who is called a monkey is more likely than an American to become angry.

Scientists often treat a novel scientific advance as a fruitful trope, or metaphor, for body, brain, or mind. For example, Descartes regarded the machine as a metaphor for bodily function; Freud exploited the metaphor of energy for emotional processes; twentieth-century scientists were friendly to a computer metaphor for thought; and contemporary investigators, awed by the recent advances in neuroscience and genetics, treat modularity as a metaphor for psychological functions. Each of these metaphors is misleading, for neither clocks, steam engines, computers, nor genes provide accurate models for the nature of brain processes or psychological activity. Although metaphors can be initially helpful crutches for creativity, scientists must remain eternally vigilant to the dangers of their seductive appeal.

The languages of the social sciences and humanities acknowledge the influence of tropes, but natural scientists typically ignore nonliteral meanings because they often include a perceptual representation and a feeling that resist accurate measurement and cannot be classified as true or false. Sentences that are interpreted literally are accompanied by patterns of brain activity that differ from the profiles accompanying a metaphorical reading of the same sentences because perceptual representations preferentially activate the right hemisphere. When individuals are interpreting sentences literally the left hemisphere is more active and there is less right hemisphere involvement.[21] Many neuroscientists measuring the brain's reaction to pictures of infants or monkeys assume that all the participants perceived and interpreted the scenes in the same literal way. Because they do not, there is extraordinary variation in the brain profiles provoked by most incentives. Natural scientists prefer to assign the cause of this variation to material differences in the brains of the participants, rather than to the meanings of the tropes they might have imposed on the stimuli.

A Brief Summary

Every concept has multiple features and these features can change with time. Therefore, the validity of any claim that two concepts are similar, or closely related, depends on the specific features that are presumed to be similar. An investigator should not treat one concept as equivalent to another if only a small number of all the possible features are the same. If a scientist writes that fatigue renders a person vulnerable to illness, readers need to know whether the primary feature for fatigue was the state caused by insomnia or excessive exercise, and whether the seminal feature for illness was a bacterial infection or a torn hamstring muscle.

This issue is especially relevant for the scientists who write computer programs simulating cognitive processes, an effort called artificial intelligence or AI. These programs typically consist of symbols for words without schematic representations of bodily states or the products of perception. As a result, these programs would represent the concept *animal* by listing the primary semantic features of this category, including reproduction, respiration, digestion, locomotion, growth, and death, but would fail to include perceptual schemata for a shark's attack on a person or a dog's obedience to a command and the feelings these schemata evoke. Yet, these representations are part of the average person's representation of the concept *animal.*

Many scientists studying the relation between brain and psychological states fail to honor this principle. For example, some write that activation of the amygdala in adults expecting a brief electric shock to their fingers means that the individuals are fearful. The problem with this conclusion is that scientists do not restrict the truth value of this claim to amygdalar activation in this specific situation, but imply that any time the amygdala is activated by any event that could be construed as "threatening" the person is in a state of fear. Even if adults deny feeling any fear in response to a still photograph of a face with a fearful expression, many neuroscientists assume that they are in a state of fear because their amygdala was activated. This inference ignores the equally reliable fact that the amygdala is also activated whenever a person encounters any event he or she did not expect, whether a sign of danger or a signal for food or sex. Most individuals do not encounter people walking around with fearful facial expressions; hence, it is reasonable to argue that their psychological state should be described as surprise or uncertainty, rather than fear. Moreover, the amygdala consists of several neuronal clusters with different evolutionary histories and different connections to the rest of the brain. Each of the amygdala's separate neuronal clusters displays a distinct profile of activation to different kinds of threat (e.g., a tone signaling electric shock and the smell of a natural predator produce different profiles in animals).[22] Hence, there is more than one type of "fear." It is also odd that, after puberty, men have a larger amygdala than women, but males are less, not more, likely to develop phobias and anxiety disorders.[23] We have a long way to go before we understand the relations between the sentences that describe brain function and those descriptive of psychological phenomena.

I borrow an example from the late Thomas Kuhn to make the critical point that many words used by natural and social scientists belong to different semantic networks and, therefore, are not equivalent in meaning. The French word *doux* (or *douce*) refers to the taste of honey, a soft touch, bland tasting soup, a tender memory, or a gentle breeze. The English word *sweet* also refers to the taste of honey, but, in addition, to a victory, a beloved, and the middle strings of a tennis racquet, but not to bland soup. Because meaning derives from the total network of related terms the French word *doux* and the English term *sweet* do not have identical meanings. The same conclusion applies to terms like fear, aroused, and count in the vocabularies of neuroscientists and psychologists and for the same reason.

THE INFLUENCE OF HISTORY

The balance between inquiries guided by a search for generalizations that transcend the current historical moment and those seriously influenced by the temporary conditions historical events created differentiates the three cultures. The present moment is part of two sequences that have never occurred before and will not be repeated. The oldest narrative began several billion years ago with the first living things. Although physicists believe that the nature of, and relations among, the constituents of matter present right after the Big Bang were different from those operative today, and biologists recognize that the genomes of humans who lived 100,000 years ago were both different from and less variable than those of contemporary humans, most of the problems natural scientists pursue are affected less seriously by the vicissitudes of time than those posed by social scientists and humanists.

The later sequence began about 10,000 years ago when human populations began to increase in size and to leave some record of their social organization, experiences, and skills. This narrative is characterized by changes in beliefs, sources of uncertainty, and social organizations. Although many social scientists seek to understand the universal human phenomena of perception, memory, language, emotion, learning, group formation, and affiliation with principles that are not restricted to the current historical moment, an equally large group probes phenomena more seriously influenced by current societal conditions.

The most important changes in Europe and America during the hundred years from 1760 to 1860 were the emergence of industrialization, capitalist economies, and a serious rise in the sizes of cities and the number of urban poor. The popular explanation of the latter fact emphasized social conditions. Hence, proposals for reform centered either on voluntary changes in political and economic structures or on the more radical revolutionary agenda of Karl Marx and his disciples. Because most citizens recognized the difficulty of creating more benign settings they were eager for an alternative interpretation that might mute the uncomfortable feeling produced by the violation of their sense of social justice. Darwin's concept of natural selection supplied the needed therapy and the advocates of evolutionary ideas began to argue, especially after 1880, that the marginalized poor, as well as the insane, alcoholics, prostitutes, and criminals, were biologically less fit. This rationalization, which gained in persuasive power over the next 30 years, lost its appeal in America after a small but vocal group of eugenicists proposed sterilization of the insane and severe restrictions on immigration. The hopes of liberal Americans searching for a rational challenge to the eugenics movement were answered by Ivan Pavlov, the American behaviorists, and Freud's disciples. These scholars resurrected an earlier emphasis on social experience as an alternative explanation of the unwanted psychological consequences of a laissez-faire economics supported by the assumption that social Darwinism was loyal to nature's intentions.

American social science emerged in universities toward the end of the nineteenth-century under the umbrella of Darwinian ideas and only a few decades after scientists had discovered relations between the site of an experimental lesion of an animal's brain and the nature of the subsequent compromise in its behavior. These scholars had a choice between looking inward to the individual psychological functions that emerged from brain activity and might be inherited, or outward to the changing environmental and social forces that required new forms of adaptation. Not surprisingly, most selected the former problem. The initial cohort of German psychologists, many of whom had mentored the first American professors, also had chosen the former theme in their studies of the nature of human consciousness, especially the state created when a person detected a change in the stimulus surround, and assumed that this process was lawfully related to patterns of brain activity they were unable to measure. Although asking adults sitting in a quiet room to say whether they detected a change in the loudness of a sound or the brightness of a light is relatively easy to do, the child's development of motor coordination and language, memory for past events, and quality of reasoning are also amenable to laboratory inquiry. I suspect that conscious awareness of a change in sensation was the favored topic because it could be related to the physical metrics of intensity of sound and light and could be regarded as a direct product of brain processes. Thus, this phenomenon satisfied the natural scientists' criteria for a legitimate target of inquiry.

However, the next generation of Americans had more pragmatic interests and were able to honor the stance of objectivity demanded by the natural scientists by studying the learning of new habits through acquiring associations between stimuli and responses. This turn allowed investigators to follow Ivan Pavlov and to design experiments with animals that could not be implemented with humans. The focus on learning also satisfied the nation's need to believe that education would hasten the assimilation of the large numbers of European immigrants. This movement, called behaviorism, lasted until the 1960s, when its inability to explain many human cognitive processes could no longer be suppressed, and it was replaced with a return to the study of human mental functions. But this time the research strategy avoided subjective phenomenology by using analytic probes of perception, memory, and decision making. By the 1970s scientists could take advantage of technological advances denied to William James and many decided that discovering the correlations between psychological processes and brain activity would illuminate the former. The interval between the first psychological experiments and current reports contained three important ideological changes.

Physical stimuli became psychological information; the concept of human will, along with understanding and emotion, was parsed into the separate functions of perception, attention, planning, regulation, and anticipation; and the initially controversial assumption of minimal differences between animals and humans in complex psychological properties became dogma.

A significant change in world view occurred during the interval from 1890 to 1920 when scientists and the educated public began to accept the idea that uncertainty and probabilistic outcomes were nature's plan and the traditional belief in determinism a naïve idealistic vision. The changing probabilities of rare events provide a persuasive example of the effects of historical change. The probability that a group of terrorists living in cities thousands of miles from a planned target of attack could successfully coordinate their efforts, as they did on September 11, 2001, was greater in 2001 than it would have been 100 years earlier because of the availability of airplanes, the Internet, and cell phones. These inventions allowed Osama Bin Laden and his accomplices to accomplish their goal. A principle in a formal model called network theory, which refers to the pattern of connections among a set of nodes, states that when the ratio of the number of connections between nodes over the number of nodes reaches 0.5 or greater, a new structure is formed and novel phenomena emerge. The planes, the Internet, and cell phones generated new social phenomena. Conversely, some events became less probable because of the increase in communication networks. Because the world's governmental organizations concerned with health are more interconnected today than they were in 1918, the probability of a pandemic influenza killing many thousands of Americans is less likely today than it was during the flu epidemic of 1918.

The effects of history on the research themes of social scientists are seen in the changing popularity of topics in academic journals. At the end of the nineteenth century, some British physicians and psychologists believed that any form of contraception was injurious to health. Bertrand Russell was given this warning when he married and took it seriously. Many sociology papers published at the end of the nineteenth century discussed the undesirable consequences of industrialization; whereas, papers of the 1930s dealt more often with miscegenation between members of the Black and White races. Two decades later, before the Civil Rights movement of the 1960s, social scientists studied the ethnic identity of Black children by showing them black and white dolls and asking them which one they would prefer to be; contemporary psychologists measure the unconscious prejudices of the majority toward minority groups.

Freud's bold predictions of the dangers of a frustrated oral stage prompted research on the later consequences of nursing compared with bottle feeding of infants and he would have disapproved of contemporary psychiatrists replacing his Oedipal complex with the concept of ethnic identity in order to understand ego development. Contemporary child psychologists who know little about the Puritans write that harsh punishment of young children is always harmful. If they had studied the memoirs of Puritan parents, and the descriptions of the development of their children, they would have realized that the effects of harsh socialization practices always depend on the child's interpretation of the reasons for the parental strictness and that interpretation varies across time and culture. If a child interprets parental punishment as reflecting the parents' affectionate wish that they develop good character, rather than as a sign of an angry or hateful attitude, the consequences need not be malevolent.

The early themes, like clothes that are out of fashion, have been replaced with investigations of subjective well-being, the implications of a secure or insecure infant attachment to a caretaker, mental illness, and the effectiveness of interventions designed to alleviate the distress of psychiatric symptoms. The recent increase in the number of papers on a homosexual life style reflects the influence of historical change on a psychological function as fundamental as sexuality.

Unlike a gay orientation in men, the increase in close, same-sex friendships between women was aided by changes in the economy that placed large numbers of working women together in cooperative work settings that occasionally led to emotional relationships that developed into sexually intimate affairs.[24] I cannot imagine a paper in any nineteenth century social science journal that described the personalities and life histories of women who had been sexually assaulted by a gang of young men, although articles on this theme appear in contemporary journals.

The interests of philosophers do not escape the historical moment. If European merchants had not wanted to be free of the ethical demands Christianity imposed and intellectuals had not wished to reject John Locke's emphasis on knowledge as sensory based, Kant might not have constructed a rational system in which freedom was a keystone resting on a vault of reason. Few philosophers writing 500 years ago would have accepted the contemporary beliefs that there are neither absolutely evil acts nor absolute truths; all humans are entitled to equal dignity; human will is fragile; and there is no determinism in nature, only a range of probabilities.

A survey of papers in the British journal *Mind*, a technical publication read by philosophers and psychologists founded in 1876 to bring philosophy closer to the physiological psychology that was in ascendance, revealed that ethics, aesthetics, truth, and phenomenal consciousness dominated the early issues. However, soon after physicists announced their discoveries in quantum mechanics and relativity, papers on reductionism, time, and space became more popular. Twenty-five years later, when psychological ideas were ascendant, articles on Freud, memory, and the relation between brain activity and psychological events appeared. Some papers relied on evidence from adults playing the Prisoner's Dilemma game, rather than on a philosophical argument, to defend the desirability of promoting the common good. Unfortunately, before any of these problems was solved, the next cohort of scholars turned their attention to a new source of angst or controversy that history had created.

The problems probed and solutions offered by social scientists and humanists are more constrained by their historical moment than those of the natural sciences. If late nineteenth-century Europeans had held a more permissive attitude toward sexuality, Freud might not have written that repression of sexual urges was the primary cause of all neuroses. If the next generation of Europeans had not been rendered despondent by the shattering of illusions at the end of World War I and the reduction of mind to a set of mechanical parts, few would have questioned the possibility of attaining ideal states and Jung might not have argued that a spiritual outlook was needed to attain a form of Nirvana. If large numbers of American men raised in working-class families who served in World War II did not have the opportunity to attend college, Erik Erikson's suggestion that all persons must solve the difficult problem of "finding their identity" would have been met with a puzzling, or lukewarm, reception. Had working mothers and divorce rates not increased dramatically in the twentieth century, John Bowlby's theory of attachment might not have gained popularity. Each of these original ideas required history to arrange a special constellation of conditions. Although a new apparatus often leads to significant observations and new concepts in the natural sciences, social conditions that alter the existing arrangements of people and their motives, beliefs, emotions, and actions are more important sources of fresh ideas in both the social sciences and the humanities.

PATTERNS OR FEATURES

Scientists, like everyone else, are biologically prepared to categorize experience in terms of the features or functions of "things" and to describe these objects with nouns modified by adjectives, adverbs, or predicates; for example, large molecules, predatory animals, or anxious adults. However, a molecule can also be described as a pattern of features that include its mass, melting point, and ease of combining with other substances. A single muscle strand in the hand can participate in patterns of motor action as different as reaching for a cup, communicating to another to stop, or waving to a friend.[25] The terms *dog* and *cat* are intended to name two different patterns of organs, physiologies, genes, and usual behaviors and, therefore, represent two distinct categories. An investigator who described only the separate features or functions referring to visual acuity, size of visceral organs, proportion of shared genes, and degree of sociability with humans would be tempted to suggest that dogs and cats are only quantitatively different and can be placed on a common scale. But two species with similar average values for visual acuity or size of the stomach could differ in the total pattern of features each possessed.

Scientists who study the relation between brain activity and psychological events have a choice between emphasizing the average activity in single neurons, or in a localized cluster of neurons, on the one hand, or the patterns of synchronized activity involving many millions of interconnected neurons in different locations. The latter strategy is likely to prove more fruitful in studies of the relation between brain and mental states because all psychological properties are the product of patterns of reciprocal activations and inhibitions of neuronal clusters in varied sites. The task of judging which of two Arabic numbers was numerically larger, brighter in illumination, or printed in a larger font size provoked three different patterns of activation and the activation of any single site did not discriminate among the three task assignments. Even the odors of cats and foxes, which are signals of danger for rats, evoke different patterns of brain activation.[26]

Most neuroscientists recording the wave forms in the electroencephalogram usually compare the response to different events or the reactions of different people by computing the average magnitude of a single waveform rather than the pattern of magnitudes for the four or five waveforms generated during the first second. The human brain is prepared to react to both features and patterns. One set of neurons in the visual cortex is responsive to the edges of objects; another selectively responds to colors; another to movement, and another to the pattern of the object. Thus, it makes no sense to ask whether the contour of the nose or the pattern of the face is more fundamental. The auditory cortex is also prepared to process patterns, for example, the ratio of the fundamental frequencies of two musical notes heard simultaneously. If the ratio of the higher to the lower frequency is 3:2, the sound is perceived as pleasant; if the ratio is 16:15, the sound is dissonant and unpleasant.

Economists like to compare nations on the single feature of gross domestic product rather than on a pattern that includes form of government, freedom of expression, life span, and ethnic diversity. Psychologists, too, usually compare genders, ethnic groups, or psychiatric diagnoses on single features, such as a particular gene, hormone level, heart rate, or brain state, instead of patterns of genes and hormone levels. The pattern of change in the stress hormone cortisol over the course of the day, for example, is a more sensitive index of its heritability than a single measure of cortisol level in the early morning or late afternoon.

When objects or events have different histories, it is usually more profitable to compare their patterns; when they share the same origin it is often more useful to attend to their features. Frogs and monkeys have two eyes and four limbs, but because their embryological developments are different, few biologists compare the limb lengths or eye diameters of the two species. Natural scientists prefer to measure separate features because they are more easily described by numerical scales that lend themselves to elegant mathematical tools. One can arrange a triangle, rectangle, and circle on a single numerical scale of area, or treat the three as distinct patterns constructed in different ways. Unfortunately, there are too few metrics for many important biological and psychological patterns and it has proven difficult to invent a set of instructions that a computer program could use to generate these patterns. That is one reason why the evolutionary biologists of the last century preferred to look for the separate genes that contributed to an adult phenotype rather than the genetics controlling the emergent patterning of the embryo. These latter genes differ from those that contribute to the adult traits.

Biologists like to write that humans and flies share a large proportion of the same genes, rather than note that the arrangements of these shared genes are different in the two species. Even the biological category *male* contains two different patterns. One class of estrogen receptor mediates the development of masculine features in the male fetus, especially the testes and penis, and a second class of receptor prevents the development of feminine features in the unborn boy.[27] Thus, there are two biological categories of men: one is high on male features and low on female traits; whereas, the other type is high on both male and female features (e.g.) a male genital combined with the more feminine properties of a round rather than a square face, a less prominent chin, less body hair, and slightly thicker lips). There is not one continuous scale of maleness.

Social scientists and humanists study many phenomena that are best described as patterns. Historians who write about the Enlightenment in eighteenth-century Europe or the classic period in lowland Mayan culture in the eighth century understand that these terms refer to unique arrangements of ideas, symbols, institutions, and practices with a special history in a particular place. Japan, England, and the United States share many political and institutional features, but sociologists treat these societies as patterns because they have different histories. When the writers Czeslaw Milosz and Witold Gombrowicz confessed to feeling ashamed of their nationalities (Milosz was Lithuanian and Gombrowicz was Polish) readers understood that their emotions were the historical products of distinct arrangements of thoughts and feelings and should not be regarded as similar to the shame felt by an adolescent who had been caught shoplifting. Types of personality and pathology are also patterns.

Patients who experience both anxiety and depression are less likely to be helped by therapeutic interventions than those who only experience depression. Although adolescents arrested for a crime share a single feature, they should be assigned to different categories based on their ethnicity, life history, and impulsivity.[28]

A rigid reliance on either single features or patterns is accompanied by distinct explanations and methods of inquiry. The former strategy, preferred by many natural scientists, renders flies and humans only quantitatively different; the second, preferred by humanists and social scientists, implies that the two forms are qualitatively different. The problem of interest and the web of ideas that is its theoretical home determine whether a vocabulary of features or patterns is employed.

Scientists often search for a particular phenomenon or living form that is a perfect model for a diverse set of events on the assumption that the essential features of the model are shared by a large number of related objects. Biologists chose the bacterium *E. coli*, the fruit fly *Drosophila*, and the worm *C. elegans* as models for genetic processes applicable to humans. Social scientists selected the Prisoner's Dilemma game as the model for economic transactions and the decisions of the political leaders of America and the Soviet Union during the Cold War. Anthropologists had thought that the baboon was the perfect model for human social behavior. John Bowlby and Mary Ainsworth were convinced that behavior in the Strange Situation was a good model for an infant's emotional attachment to its caretaker, and Freud believed that the case history of Little Hans was representative of the mechanisms that mediated all phobias. In all of these cases, investigators eventually learned that each phenomenon had unique features that were not shared with other more complex events they wanted to understand.

However, some models have advantageous consequences because later research with the model leads to unexpected methodological advances. For example, study of *E. coli* and *Drosophila* resulted in discoveries that allowed cloning of the sheep "Dolly." Thus, picking a model organism or procedure can be useful, even if the original hope is not fulfilled. The task is to figure out which features of a model are shared with other phenomena one wishes to understand and which are restricted to the animal, process, or procedure chosen. The answer to this puzzle is rarely obvious when inquiry begins.

THE MENTAL TOOLS

Scholars vary in their reliance on three types of mental structures when they describe or explain a phenomenon: mathematical concepts and equations, semantic networks, and perceptually based schematic representations. The original meaning of the $\sqrt{2}$ in ancient Greece contained a perceptual feature, for it referred to the length of the hypotenuse of a right angle triangle with sides of unit length. Most contemporary students of mathematics understand the $\sqrt{2}$ to represent the abstract concept of an irrational number without a schematic element. Rosalind Franklin's antipathy toward the construction of mechanical models may have been one reason why Crick and Watson, and not she, discovered the structure of DNA. The imaginations of the two men were enhanced when they could see the possible spatial relations among the four bases and think about them in schematic form.[29]

The terms *concrete* and *abstract*, which describe types of semantic concepts, should be replaced with a description of the differential proportion of semantic and schematic representations of an event. That is, the networks called concrete always contain schemata (e.g., the perceptual representation of an apple is usually part of the network for fruit). The network for abstract concepts like *metaphysical* have few if any perceptual schemata. A schematic feature was added to the concept *gene* when Crick and Watson drew its structure in their famous 1953 paper. The addition of a schematic node did not make the concept *gene* more concrete and less abstract; rather, it added a schema to what had been an abstract semantic network.

Semantic and schematic representations have different organizations. One salient difference between them, at least for English speakers, is that the representation of the usual context in which an object is encountered is associated with the schema for the event. The schema for a bird, for example, is likely to be linked to schemata for trees, lawns, and the sky. By contrast, the organization of semantic networks emphasizes conceptual hierarchies, antonyms, and the features of concepts. Hence the word *bird* is more closely associated with semantic nodes for robin, animal, and wings than to nodes for trees, lawns, and the sky. Schemata do not have opposites – the schema for a sweet taste is not linked to one for sour – and they do not nest into hierarchies. Moreover, a schematic prototype, for example, for a friend's face, makes it difficult to discriminate between subtle alterations in the friend's facial expressions because the agent attends to the whole face rather than to the separate parts. By contrast, a woman's semantic network for a friend, which includes name and many traits, does not imply that she cannot distinguish among the moods of the friend.

During early childhood, schemata for perceptual experiences are often established before semantic forms. One-year-olds have schemata for the pair of eyes and single nose of the face before they learn the semantic forms for the cardinal numbers. Moreover, schemata often influence related semantic networks, but the opposite is less common. That is, the schemata for a class of experiences is less likely to be influenced by semantic forms. This asymmetry finds support in adult estimates of the time that lines of varied length remained on the screen of a monitor (the durations ranged from 1 to 5 seconds). The semantic estimates of time on the screen were influenced by the length of the line – the longer the line the larger the time estimate. But the estimates of the line lengths were not affected by how long the line remained on the screen.[30] This observation implies that the semantic concept *time* is linked to schemata for the length of a line or the distance between two locations, but the schemata for length or distance are less often influenced by the semantic concept for time. Although Einstein's equations in the theory of general relativity combined space and time in a "space–time warp," most minds keep these two ideas separate.

Most three-year olds who can recite the numbers from one to ten do not yet understand that the word "ten" refers to a larger quantity than the word "five", and their schemata for ten or for five cookies on a plate would not be affected by hearing someone speak the words ten or five while they were staring at the cookies. Thus, the young child's schema for five cookies on a plate does not mean that he possesses a concept for number. The recitation of the numbers from one to ten resembles the child's ability to recite the names of the notes of the musical scale. Both are the result of the rote learning of a sequence without semantic meaning. However, the schemata for varied quantities does help children learn the meanings of the cardinal numbers during the preschool years.

Humans learn associations between the schema for the top of a tree and the semantic networks for the future and the Divine, and between the schema for the bottom of a tree and the semantic networks referring to the past and the devil. The schemata for the sensory states that accompany a sweet food or the warmth of a fire are part of the semantic network for good; a bitter taste and pain are components of the semantic network for bad. It is likely that the feeling of distress produced by the acts of an aggressor toward the self or another person participate in the semantic network for fairness and justice. Put plainly, perceptual representations of experience, which develop first, are often exploited as scaffolding to amplify the meanings of abstract semantic terms. College students who are not professional neuroscientists are somewhat more likely to believe the conclusion of a technical report if it contains a picture of a brain than if it only presents the data. Jurors, too, are vulnerable to classifying a person on trial for a serious crime as mentally ill, and therefore not fully responsible, if the defense lawyer presents a picture of the defendant's brain and points out that it deviates from the brains of the majority. Perhaps that is why string theorists writing for a general audience add a drawing of what a string might look like, even though the authors know it is impossible to illustrate the mathematical equations that represent strings. As an adolescent I believed the verbal and mathematical arguments declaring that the Earth was round, but suspect that I could have been persuaded to change my mind if new evidence led scientists to alter their opinion. But after I saw the picture of our planet taken from a spacecraft my commitment to its round shape became irreversible. Pictures are indeed worth a thousand words.

Mathematical Concepts

The differential explanatory power of the three types of mental tools was articulated in Europe in the seventeenth century after the mathematical propositions of Descartes and Newton proved so successful. Natural philosophers began to claim that, whenever possible, equations should replace illustrations and semantic descriptions. Mathematical forms have proven extremely powerful in physics and chemistry. Werner Heisenberg's creative use of algebraic matrices allowed him to discover the famous uncertainty principle. Many physicists, including Einstein, initially resisted Heisenberg's argument because it denied strict determinism, was difficult to imagine, and there were no words that described accurately the physical events the matrices represented. Niels Bohr, Heisenberg's mentor, preferred combinations of semantic concepts and schemata of electrons orbiting an atom's nucleus of protons and neutrons. Surprisingly, Bohr's research notebooks contained only pictures and words and no mathematical calculations. When Bohr first learned of the fission of the uranium atom in 1939, he attempted to understand this surprising event by imagining a spherical drop of water (representing the atom's nucleus) being deformed by bombarding neutrons into the shape of a peanut. Bohr's insight into the relation between the spectral lines emitted by a heated atom and the energy of its orbiting electrons was the product of an intuition rather than the manipulation of equations.

A comment by Paul Dirac, a British physicist who also thought in mathematical terms, reveals the contrast between the tools preferred by Heisenberg compared with Bohr. Dirac, who had visited Bohr in Copenhagen in 1926, was frustrated by Bohr's insistence on using arguments based on qualitative semantic concepts, rather than the less ambiguous mathematical equations that the British scientist found easier to manipulate mentally and far more satisfying. While visiting an art exhibition with Bohr, Dirac noticed a dark gray, ambiguous spot of paint that Manet had placed near a boat in one of his paintings, and remarked, "This spot is not admissible."[31] George Gamow, a physicist who conceived of DNA as a code before Crick and Watson described its structure, provided a persuasive example of how a scientist's preferred tools of thought can interfere with a discovery. Because symmetry (meaning a mathematical operation that does not change the form of an object) is a seminal concept in physics, Gamow assumed that it made no difference whether messenger RNA read the DNA molecule from left to right or right to left. However, DNA has a polarity and messenger RNA reads the DNA code in only one direction. Thus, Gamow failed to infer the correct molecular structure of this molecule. Eugene Wigner, another physicist who thought in mathematical structures, argued that his analyses implied the absolute impossibility of life forms emerging from chemical elements. Lord Kelvin, arguably the nineteenth century's most respected natural scientist, intimidated Darwin by suggesting that his mathematical analyses proved that the Earth could not be old enough to support Darwin's theoretical claims.

Some children have great difficulty separating mathematical representations from the more familiar representations for words. Carl Jung, who provided an example of this psychological block, recalled his profound inability to accept the argument: If $a = b$ and $b = c$ then *a* = *c* because he always replaced the letter symbols with semantic concepts and rebelled against the possibility that if cats = pets and pets = dogs then cats = dogs. "My intellectual morality fought against these whimsical inconsistencies, which have forever debarred me from understanding mathematics."[32] Jung's difficulty is understandable. The notion that a letter in an equation can represent a range of numerical values for any class of events is only 12 centuries old. Moreover, some languages assign different names to equivalent quantities of different kinds of objects. Residents of the eastern Fiji islands, for example, award different number names to 100 canoes (bola) and 100 coconuts (kora).[33] I take the late emergence of algebra in human history as implying that, unlike the manipulation of semantic or schematic representations, reasoning with abstract mathematical concepts is not a biologically prepared competence that comes easily to human intuition. Remember, geometry preceded algebra by many centuries. Bertrand Russell's experience of falling in love with mathematics at age eleven after he read Euclid for the first time is uncommon.

Not all events or relations between observations are amenable to a mathematical description. The relation between the composition of the wooden cask in which a wine is aging and the bouquet and taste of the wine is one example. Furthermore, a mathematical relation between or among concepts does not explain the relation. Consider an apple on a branch six feet above the ground falling to the earth. One can film this event, describe it in words, or write the mathematical equation $s = \frac{1}{2} gt^2$ indicating that the distance the apple traversed equals one-half the product of the gravitational force and the square of the time falling. None of the three descriptions explains why the apple fell the way it did; physicists do not yet understand the nature of the gravitational force. However, the mathematical model has the advantage of greater clarity and the promise of being applicable on all occasions when an object falls to the ground. Thus, most scientists agree that mathematical statements are always preferable to the other two forms. Unfortunately, many observations in the biological and social sciences cannot meet the conditions required for faithful adherence to the imperative for mathematical statements.

It is important to distinguish between a mathematical statement that attempts to describe a rich set of evidence, on the one hand, and a mathematical model that contains a priori concepts invented to explain an old or to predict a new phenomenon, on the other. Kepler's equations were intended to describe an extensive set of observations on the orbit of Mars. By contrast, the equations of string theorists contain the a priori notion of packets of energy oscillating in ten dimensions that have not been observed. A mathematical model for a class of events is more fruitful when it accommodates the evidence, does not make too many assumptions that violate known facts, and defines its concepts intrinsically rather than by outcomes or consequences. For example, the physical concepts of time and distance in Newton's equations for a falling apple have fixed definitions that are independent of the outcome of the falling object, as well as the distances and times for other apples falling from the same tree.

These requirements may seem obvious, but unfortunately many mathematical models in evolutionary biology and economics, two fields that rely on formal models, fail to meet them. For example, some models in evolutionary theory assume infinitely large breeding populations and no mutually interactive influences among an animal's genes (called epistasis). Both assumptions violate what is known to be true. One evolutionary model, which is presumed to stipulate an animal's optimal behavioral strategy, contains five concepts: "the cost of fighting" a competitor for "a resource" (food or niche) compared with "fleeing," the "value" of the resource, and the implications of each behavioral strategy for the animal's "inclusive fitness."[34] Each of these concepts is defined functionally rather than intrinsically.

A biologist observing two hawks approaching the same prey from a distance cannot state, before the two birds meet, the cost to fitness of fighting versus retreating, or the change in each hawk's fitness following a decision to fight or to flee. Moreover, if the resource were a niche for nesting rather than food, the value, cost, and fitness magnitudes in the equation would change. Yet, surprisingly, evolutionary biologists ignore these details in their abstract models. The failure to specify whether what is gained or lost is food, access to a mating partner, or a nesting site renders the equations ambiguous and questions their generality.

Similar problems compromise the value of many economists' models. Although I consider this issue in detail in Chapter 4, an example might be helpful here. On the first warm June day after a cold spring millions of workers will need to choose between taking the day off or honoring their obligations to an employer. Economists rely on the concept of *preference* in these situations. The workers have to choose between two different utilities that can be measured only after each worker has acted. Economists first need to find out the proportion of workers who did or did not go to work on that day, and, after the fact, invent a mathematical model for the situation.

This limitation is reminiscent of the frustration of the behaviorists of the last century who relied on the concept of *reward*, but did not have an intrinsic definition that permitted them to know ahead of time which events possessed this special property. Psychologists had to wait and see what stimuli or situations animals worked to obtain and, after the fact, call them rewards.

Consider what is admittedly a caricature of the economists' models. Investigators could measure in a sample of 1,000 men over the course of a year the proportion of occasions when each argued with or accommodated to the requests of a wife, employer, or close friend. Suppose that the evidence indicated that, on average, the men argued more often than they accommodated when with their wife, accommodated more with their employer, but showed no preference with a friend. It would be an error to write a general model stating that the utility of accommodating outweighed the cost of arguing, or that the utility of arguing was an average of the proportion of occasions they chose that strategy with all three targets. Rather, the preference for one strategy over another varied with the specific social context. This level of specificity is missing from the models in economics and biology.

Many economists ignore fruitful explanations that are not presented as formal models, preferably mathematical in structure, because they believe that "economics isn't defined by its subject matter, but by its way of thinking."[35] Robert Lucas, a Nobel laureate in economics, is more dogmatic on this issue, "Economic theory is mathematical analysis. Everything else is just pictures and talk."[36]

Equally important, the models of biologists and economists assume that the arithmetic rules of addition, subtraction, multiplication, and division are legitimate operations on the numbers assigned to measures of their concepts. However, this assumption can be questioned. The physical concept *mass* meets the mathematical criteria that allow scientists to add the masses of two different objects (say a log and a stone) to arrive at a new value. These criteria include the presumption of ratio scales (e.g., a mass of 10 kg is twice that of 5 kg and a mass of 200 kg is twice that of 100 kg). However, it is less obvious that the economists' concept of *utility* meets these requirements. Economists treat the arbitrary scale of numbers measuring a utility as if it had the properties of mass when they, for example, implicitly add the utility a father anticipates from purchase of a new car for weekends and holidays to the utility assigned to the father's intention of letting his daughter use the car to commute to work. Because these utilities are psychologically different it is not obvious that the sum of the two values is proportional to the values of each utility, which is true for mass. It is possible that the father's belief that his daughter will use the car five days a week reduces the utility he anticipated from using it on weekends. No concept in the formal models of economists or evolutionary biologists has the mathematical properties possessed by the physicists' concept of mass.

Semantic and Schematic Forms

Humanists and social scientists rely mainly on networks of semantic and schematic forms, rather than on mathematical concepts, when they brood about a problem and propose a solution. The networks for concepts such as ideal, Enlightenment, society, identity, and conflict are not amenable to mathematical treatment. Semantic and schematic networks have the advantage of inviting scholars to think in terms of patterns of elements; mathematical equations tempt investigators to think in terms of continuous functions for separate features. Most rare events are discrete patterns resulting from a combination of several low-probability conditions occurring simultaneously, not unlike perfect storms. However, at some point during a solution process most members from all three groups are likely to activate some perceptual representations of the events that their equations and semantic concepts are intended to describe. Even string theorists, who rely on mathematical statements, draw pictures to illustrate their understanding of a string. All three mental forms are useful; the trick is to know when to use each one and to avoid using the wrong tool at an inappropriate time.

Tolerance for Ambiguity

Mathematical, semantic, and schematic representations vary in the ambiguity of the knowledge they convey. The intellectual disciplines can be arranged on a continuum representing the ambiguity of their descriptions and conclusions, with mathematics and physics at one end, the social sciences in the middle, and the humanities at the opposite end. Because individuals differ in their tolerance for ambiguity, it is likely that both personality traits and culture affect the domain chosen for a scholarly career. Some youth inherit a biology that renders them especially vulnerable to an uncomfortable feeling of tension when they are uncertain over the future and there is ambiguity surrounding the best behavior to display when they have a choice. Many adults with this personality trait were unusually shy as young children.[37] Bertrand Russell, a shy youth who suffered from nightmares, devoted his career to removing ambiguity from philosophy.

THE MEANINGS OF TRUTH

The distinctions among the three mental tools and the level of ambiguity in evidence and conclusions bear a relation to the concept *truth* and the related notions *correct*, *valid*, *coherent*, and *right*. Every scholar wants his or her intellectual products to meet the criteria for at least one of these terms. Rather than offer definitions, which will certainly provoke controversy, it is more useful to focus on the referent. That is, what do natural scientists, social scientists, and humanists point to when they claim they are communicating a true idea? The four usual referents are: a consensual observation of an event outside the self that can be affirmed by others (e.g., the moon is or is not present in the sky); the consistency of a logical or mathematical argument (e.g., if velocity equals the ratio of distance over time then distance equal the product of velocity and time); the meaning coherence among the semantic networks of a narrative (e.g., a historian's suggestion at the end of a narrative of World War II that Churchill did not attend Roosevelt's funeral because of his lingering anger over being embarrassed by Roosevelt during their meetings with Stalin has a claim to truth if this idea strikes most readers as coherent with the complete text); or a compelling feeling (e.g., the feeling accompanying the thought that parental sacrifice for a child is right and abuse is abhorrent).

The members of the three cultures differ in the frequency with which they rely on one or more of these four referents. Most natural scientists trust only the first two; social scientists the first and third; humanists rely on the last two. Although correspondence between an idea and evidence is a criterion for both natural and social scientists, the objectivity of their evidence often separates the two groups. Natural scientists worry about the subjective bias a human observer imposes on an event and demand that a machine record the events of interest, even though each machine's structure imposes a special set of biases. Social scientists are more often concerned with the meanings of verbal statements or actions. Because machines cannot record meanings, social scientists rely on consensual agreement among trained experts as a way to protect against the biased perspective of a single observer.

However, the introduction of powerful machines that expose properties lying deep beneath the surface of a phenomenon, which linear accelerators, space telescopes, and brain scanners do, has created a problem for the natural scientists committed to objectivity. Nineteenth-century scientists had assumed that the observations that all reasonable judges could agree upon were the foundation of a science. Everyone with normal vision would agree with Newton's observation that light passing through a prism splits into a rainbow of colors. No special expertise was required for this perception. However, interpreting the extraordinary complex corpus of data resulting from smashing protons into one another at speeds approaching the velocity of light requires special training, and all scientists do not detect the same evidence or agree on its meaning. As a result, physicists have been forced to accept a consensus among many experts interpreting what is meaningful in a corpus of data produced by a machine. This practice means that the differences between natural and social scientists in the definition of objectivity have become smaller than they used to be and the meaning of a concept has become more dependent on the theory that is its home.[38]

This section should not end without some reference to the influential writings of the German social scientist Jürgen Habermas, who is more concerned with the meaning of rationality than with the definition of truth, valid, coherent, or right. Habermas holds out the promise of an unborn social science that mediates between, and synthesizes, the positivism of the natural sciences and the semantic hermeneutics of the humanities.[39] However, his definition of rational refers to the degree of agreement within a community over the validity of a belief, rather than the logical consistency of an argument. Habermas has been criticized for trying to unite the two distinct traditions of American pragmatism with Wittgenstein's emphasis on the importance of consensual understanding. Put plainly, according to Habermas, a person is said to have a rational idea when he or she can communicate it effectively to at least one other person. The problem with this definition is that it means that Einstein might not have had a rational idea the moment he thought about a moving massive body altering the space–time warp if he were unable to communicate this concept to a colleague, but the seventeenth-century residents of Salem, Massachusetts did possess a rational concept when they talked about the reality of witches. The writings of anthropologists and historians reveal that many consensual beliefs that were judged as rational turned out to be empirically false. It will prove more worthwhile, therefore, to argue over the definitions of true, valid, coherent, correct, and ethically right than to worry over which ideas are rational. Moreover, rather than quarrel over which intellectual group has a privileged access to any of these concepts, we should acknowledge the different meanings these abstract ideas can assume.

WHAT TO STUDY?

Long before science became a possible career for youths, most scientists chose to probe phenomena that appeared to be regular, amenable to measurement, and inexplicably mysterious. The changing locations of the stars and planets, falling objects, magnetism, blood flow, and disease were consistent targets of inquiry because they met these criteria. Human behavior was not a popular subject because it lacked predictability and ease of measurement. Scholars can pursue an inordinately large number of questions and the ones selected depend on many conditions that change over time, including a dominant theoretical view, cultural setting, a new technology, or a social crisis.

Life scientists tend to select one of two targets of concern. One group wants to understand the most fundamental, or ultimate, factors that contribute to an outcome. The second is more interested in understanding the cascade of intermediate processes leading to an outcome, and assumes it is influenced by the specific contexts in which each phase of a cascade occurs. This tension is present in the contrast between the biologists who are concerned with the genetic differences among the adult members of a species and those who believe that understanding the adult form requires study of how genes, in combination with other conditions, produced each animal's form during the stages of embryological growth. Psychologists are divided between those who search for the genes that contribute to specific psychological traits and those who believe it is necessary to know each person's history because most genomes lead to different outcomes in individuals with different histories. The two groups ask different questions, perform different experiments, and rely on different explanatory concepts. A judge who asked the bank robber Willie Sutton, "Why do you rob banks?" wanted to know why he robbed banks rather than work at a lawful job. When Sutton answered, "Because that's where the money is," he assumed the question was, "Why do you rob banks rather than grocery stores?"

The ideal incentive for intellectual work is an inability to understand an observed phenomenon, an inconsistency between theory and observation, or a paradox in mathematics. An important difference between natural and social scientists is that the former are more likely to brood over why the results of an experiment failed to support a theoretical prediction. Their subsequent attempts to explain the failure often lead to an important discovery. Max Planck posited the quantum in 1900 because he wished to understand why the measured energy frequencies emitted from a heated vessel, called a black body, were not in accord with the popular theory of the time.

However, there are so many reasons why an experiment in the social sciences might fail, most social scientists react to a failure of prediction by moving on to another question. For example, when the cumulative evidence indicated that a person's interpretations of ink blots did not predict their conflict over sexuality or hostility the psychologists who conducted this work did not try to understand why, perhaps by probing the relation between the interpretations offered and some other aspect of the person, but abandoned this method to pursue another question. Had they persevered they might have learned that the responses to the ink blots reflected the individual's preferred perceptual style which, in turn, was related to the personality profiles of introversion and extraversion.

Young scientists feel a palpable pressure to pursue the problems that the politically powerful members of their discipline have classified as having precedence. Conformity to the biases of these respected elders is more likely to lead to promotion and tenure than pursuing an unpopular question. Charles Townes was a rare exception, for he continued to work on the maser despite discouraging comments from senior colleagues who told him he was pursuing a useless problem. American natural scientists award priority to problems that are technically challenging, amenable to accurate measurement, require mastery of a new technology, and are likely to yield evidence that can be summarized with mathematical propositions. Investigators who conform to these criteria can demonstrate their intellectual brilliance to colleagues and superiors. Unfortunately, these criteria often compete with the complexity or mystery of a phenomenon as a basis for problem selection.

Lee Smolin, a particle physicist critical of string theory, wrote, "Achievements requiring nothing more than cleverness and hard work are valued more highly than probing thought or imagination."[40] Michael Faraday, who had little training in mathematics, was celebrated by his natural science colleagues because of his astute observations and creative suggestion that magnetism and electricity were related. A contemporary Faraday would have a harder time gaining recognition because of his inability to describe the phenomena in mathematical terms, which James Clerk Maxwell did a few years later. The current emphasis on a scientist's "brilliance" means that an investigator who uses mathematics has an edge over one who uses words because mastery of the former implies a keener mind. The aesthetic feeling generated by reading about a novel observation, even though it is not yet understood (e.g., the first descriptions of the patterns of blood flow emanating from the heart or the discovery of X-rays), differs from the feeling evoked by the admiration for an astute mind. Even though a mind is the origin of every discovery and explanation, we are usually moved more by the beauty of a photograph of a sunset than by the photographer's talent with a camera.

Nineteenth-century European society had a fairly rigid class structure consisting of a small aristocracy and large groups of middle-class professionals, merchants, and laborers. Youths planning a career in the natural sciences were sensitive to the problems their community believed should be probed and the answers that would appeal to those with status in the society.[41] The upper-middle-class German community in the late nineteenth and early twentieth centuries was attracted to complex ideas that involved whole phenomena, especially the relation between an entity and its context, and was hostile to the analyses of elementary parts isolated from their setting. Hence, early German geneticists were not attracted to the study of isolated genes or chromosomes and investigated the role of the cytoplasm and the development of the embryo. American scientists working during the same era held the opposite set of biases. They celebrated hard facts that could be affirmed with certainty and made important discoveries with the fruit fly *Drosophila*. Even though later history proved the German intuition right, the required methods were not invented until late in the twentieth century, and the discoveries these methods made possible created the exciting new domain called "evo-devo." The early cohorts of academic psychologists, also German, could have studied the acquisition of conditioned reflexes, but chose the more complex theme of consciousness instead. The pragmatic American psychologists, who appreciated that consciousness was not amenable to rigorous inquiry, selected the former problem.

The swelling in the number of scientists seeking promotion to the small number of professorships has tempted many junior investigators to become pragmatic and to pursue problems that would produce publishable results quickly. A resume listing many papers in high-prestige journals was a sign of a talented mind. Young scientists recognized, however, that significant discoveries usually required perseverance over long periods of time, without any guarantee that the prolonged effort would be successful. The more rational strategy was to conduct experiments that could be completed quickly and were likely to yield clear results. Gregor Mendel, who persevered in his studies of plant inheritance, and did not publish many papers, was fortunate. Gottlob Frege, one of the most respected logicians and philosophers of the late nineteenth-century, was not. Frege labored for decades on the logical nature of the concept of number but failed to solve the problem. Georg von Békésy, who received the 1961 Nobel Prize in Medicine for his discovery of traveling waves on the basilar membrane of the inner ear, noted in his acceptance speech that he had initially laid out a research program that he thought would take at least fifteen years to complete. It has become more difficult to find a von Békésy in the contemporary research university because the current ambience invites the adoption of a risk-averse strategy that promises many short-term gains.

A recent survey by the National Science Foundation of more than 24,000 active scientists, many of whom review research proposals in the natural sciences, revealed a discouraging picture. Only 25 percent of the proposals were regarded as likely to produce an original, transformative idea; the vast majority were judged as minimally creative because the supplicant scientists worried more about anonymous referees rejecting experiments exploring an original idea than about making a discovery of theoretical importance.[42] Mario Capecchi, one of the winners of the 2007 Nobel Prize in Medicine for his contribution to the development of mice with deleted genes (called knockout mice), submitted a request to the National Institutes of Health in the 1980s to pursue this hypothesis. The committee reviewing the proposal rejected the experiments designed to alter specific genes in mice and advised Capecchi to forget his "wild" idea.

Most scientists are aware of the poor agreement among three reviewers of a research proposal and appreciate that the more original the ideas proposed, the poorer the degree of agreement. It is no wonder then that most scientists are reluctant to initiate research that deviates too far from what is currently popular and prefer to propose a clever variation on experiments that are safe and likely to lead to a publishable result. Both the reputation of scientists and the public good would be served by restoring an earlier balance between rewarding cleverness qua cleverness and cleverness exploited in the service of a significant insight. Lao-Tzu, the Chinese philosopher of the third century BCE, reflected his culture's greater reverence for wisdom over technical expertise when he wrote, "Great cleverness resembles clumsiness."[43]

TYPES OF SCIENTISTS

It is difficult to separate the content of a discipline from the types of people who select it for a career. Youth who chose sociology or art history would be unlikely to pursue a career in molecular biology or particle physics. When economics became heavily mathematical, after 1950, college seniors who enjoyed mathematics, but were uncertain over whether they would be able to make an original contribution to formal mathematics, often selected economics because this domain allowed them to use their talents, and not necessarily because they were vitally interested in understanding the economies of nations.

It is possible to detect at least four different motivational patterns among scientists, independent of the presence of a curiosity about some aspect of nature that all four types share. Similar categories can be found in other professions. The most prevalent type in the technically demanding natural sciences tries to demonstrate his or her intellectual potency by solving a difficult problem colleagues regard as theoretically important or technically demanding with an answer that appears to be free of ambiguity. The specific content of the problem is often irrelevant because the primary goal is to demonstrate that one possesses an intelligence that deserves respect. That is one reason why many physicists who had made important discoveries early in the last century abandoned their original field for biology after reading Erwin Schrödinger's book, *What Is Life?*. Francis Crick's mentor, M. F. Perutz, was a member of this group. Schrödinger persuaded many physicists that the odds of making a brilliant discovery had become greater in biology than in physics. This goal is accomplished more easily through study of simpler, rather than more complex, forms. Hence, many biologists study bacteria and fruit flies rather than monkeys and humans and many psychologists interested in human cognitive abilities write computer programs simulating perception or reasoning that do not include perceptual representations or emotions because it is difficult to incorporate these processes in statements containing only symbols. Christiane Nusslein-Volhard, who won a Nobel Prize for her studies of embryological development, chose to study physics initially because of an interest in its phenomena. But she shifted the target of her curiosity to biology when she found mathematics too demanding because, presumably, she wanted to be able to demonstrate her talents.

Most natural scientists, therefore, resemble big game hunters whose primary motive is to track and kill an animal that is difficult to find, and often do not care if the quarry is a snow leopard, lion, or tiger. The joy comes from using one's skills and energy to solve a difficult problem, any difficult problem, that promises a minimally ambiguous answer. Charles Darwin did not know what he would discover on the *Beagle* voyage and noted in his autobiography that his primary ambition was, "to take a fair place among scientific men."[44] Darwin might have felt just as gratified had he stayed at home and, by poring over archival evidence, discovered continental drift. The Nobel laureate biochemist Albert Szent-Györgi announced the hunter's credo when he remarked that any student who "comes to me and says he wants to be useful to mankind and go into research to alleviate human suffering, I advise him to go into charity instead. Research wants real egoists who seek pleasure … in solving the puzzles of nature."[45]

The second type, more frequent among social scientists, is characterized by a deep desire to understand a particular class of phenomena, whether the behavior of infants or gorillas, or the causes of crime, schizophrenia, or racism. These scholars care passionately about a particular target of inquiry, and would be unhappy if forced to abandon the question that attracted them to science simply because the problem was too complicated and the explanation penetrated with ambiguity. These scientists resemble devoted bird watchers who have a passionate curiosity about the specific animal they are tracking. It is hard to imagine the late anthropologist Clifford Geertz abandoning the study of cultures for molecular biology or the sociologist William Julius Wilson giving up his research on minority groups to study the brain. The attitude toward ambiguity, which is often apparent in childhood, separates these two classes of scholars. The hunters shun ambiguity or, put more positively, derive maximal satisfaction from solutions that promise certainty. The bird watchers are more tolerant of ambiguity because their pleasure comes from observing and brooding about a very specific class of phenomena.

The other two types, although less frequent, are not rare. One group, with a strong motive for public celebrity, experiences a special satisfaction when they know that large numbers of strangers recognize their name and think about them as famous. The domain chosen depends on their judgment of where their talent is greatest. Young adults with this motive who select science are likely to pick a problem in which the public has a deep interest. Because most citizens are vitally concerned with the human condition, many with this personality choose the social sciences. The fourth type enjoys carrying out the routines of the laboratory: setting up an experiment, building the apparatus, gathering the data, and analyzing the observations with the most elegant analytic technique. This group feels satisfied when they implement the rituals of the scientific domain they selected. Fortunately, natural science requires cooperation from teams with diverse talents and profits from these workers in the vineyard. Although most scientists possess all four motives, these desires form a hierarchy with one usually dominating the others. Taste, which is always affected by personality, historical era, and culture, exerts a considerable influence on the discipline chosen for a career as well as the target selected for inquiry.