Mauro Formation cratering debris. Does it mean that the moon has been sectorally as well as radially heterogeneous since the time of its formation? Has volcanism occurred anywhere on the moon substantially later than 3.15×10^9 years ago (the age of the youngest mare basalt samples)? The last two Apollo missions are targeted to regions that offer the prospect of answering these questions. The most profound question of all is the origin of the moon, or more properly the earth-moon system. Apollo science has eliminated the once-popular hypothesis that the moon was captured recently (1 to 2×10^9 years ago), but beyond this the question remains unanswered. If the nature of compositional heterogeneities in the moon at the time of its accretion can be inferred correctly from chemical and petrologic studies of the present magmatically differentiated moon, this information will go far toward answering the question.

Our goal of understanding the moon, like other objectives of space research, is bound to be furthered by cooperation between the nations engaged in exploration of space. The Third Lunar Science Conference was a minor landmark in international collaboration, in that for the first time Soviet scientists reported results of their research on Apollo samples and Americans described their work with Luna 16 material, the fruits of a sample-exchange agreement concluded by the National Aeronautics and Space Administration and the Soviet Academy of Sciences last spring. We can hope this small but tangible cooperative arrangement presages an era in which joint United States–Soviet space ventures become commonplace.

References and Notes

1. "The Moon Issue," *Science* **167** (No. 3918) (1970).
2. The research summarized in this article is reported in more detail in *Revised Abstracts of the Third Lunar Science Conference* (Lunar Science Institute, Houston, 1972). It will also appear in three volumes as *Proceedings of the Third Lunar Science Conference* (M.I.T. Press, Cambridge, Mass., in press).
3. Lunar anorthositic rocks contain more than 65 percent calcic plagioclase, the remainder being calcium-poor pyroxene or olivine; lunar norite contains approximately equal amounts of calcic plagioclase and calcium-poor pyroxene. Lunar anorthosites and norites are rarely coarse-grained igneous rocks, as are their terrestrial namesakes: most examples described to date are fine-grained recrystallized breccias or igneous rocks. Lunar anorthosites are poor in radioactivity (sample 15415; 120 ppm of potassium, 0.01 ppm of thorium, 0.002 ppm of uranium); norites are highly radioactive (typically 5000 ppm of potassium, 12 ppm of thorium, and 4 ppm of uranium); basalts occupy an intermediate position (500 to 2500 ppm of potassium, 1 to 3 ppm of thorium, and 0.2 to 0.8 ppm of uranium).
4. Noritic breccias at Fra Mauro contain 4000 to 6000 ppm of potassium, 11 to 15 ppm of thorium, and 3 to 4.5 ppm of uranium.
5. For x-ray fluorescence data, see I. Adler, J. Trombka, J. Gerard, R. Schmadebeck, P. Lowman, H. Blodgett, L. Yin, E. Eller, R. Lamothe, P. Gorenstein, P. Bjorkholm, in *Apollo 15 Preliminary Science Report* (National Aeronautics and Space Administration, Washington, D.C., in press). For gamma-ray spectrometer data, see J. R. Arnold, L. E. Peterson, A. E. Metzger, J. I. Trombka, *ibid.*, in press.
6. G. J. Wasserburg, G. Turner, F. Tera, F. A. Podosek, D. A. Papanastassiou, J. C. Hunecke, in *Revised Abstracts of the Third Lunar Science Conference* (Lunar Science Institute, Houston, 1972), p. 788.
7. D. A. Papanastassiou and G. J. Wasserburg, *Earth Planet. Sci. Lett.* **5**, 361, 376 (1969).
8. R. K. McConnell, Jr., and P. W. Gast, in a paper delivered at the Conference on Lunar Geophysics held at the Lunar Science Institute, Houston, Texas, 18 to 21 October 1971.

The Nature of the Darwinian Revolution

Acceptance of evolution by natural selection required the rejection of many previously held concepts.

Ernst Mayr

The road on which science advances is not a smoothly rising ramp; there are periods of stagnation, and periods of accelerated progress. Some historians of science have recently emphasized that there are occasional breakthroughs, scientific revolutions (*1*), consisting of rather drastic revisions of previously maintained assumptions and concepts. The actual nature of these revolutions, however, has remained highly controversial (*2*). When we look at those of the so-called scientific revolutions that are most frequently mentioned, we find that they are identified with the names Copernicus, Newton, Lavoisier, Darwin, Planck, Einstein, and Heisenberg; in other words, with one exception, all of them are revolutions in the physical sciences.

Does this focus on the physical sciences affect the interpretation of the concept "scientific revolution"? I am taking a new look at the Darwinian revolution of 1859, perhaps the most fundamental of all intellectual revolutions in the history of mankind. It not only eliminated man's anthropocentrism, but affected every metaphysical and ethical concept, if consistently applied. The earlier prevailing concept of a created, and subsequently static, world was miles apart from Darwin's picture of a steadily evolving world. Kuhn (*1*) maintains that scientific revolutions are characterized by the replacement of an outworn paradigm by a new one. But a paradigm is, so to speak, a bundle of separate concepts, and not all of these are changed at the same time. In this analysis of the Darwinian revolution, I am attempting to dissect the total change of thinking involved in the Darwinian revolution into the major changing concepts, to determine the relative chronology of these changes, and to test the resistance to these changes among Darwin's contemporaries.

The idea of evolution had been widespread for more than 100 years before 1859. Evolutionary interpretations were advanced increasingly often in the second half of the 18th and the first half of the 19th centuries, only to be ignored, ridiculed, or maligned. What were the reasons for this determined resistance?

The history of evolutionism has long been a favorite subject among historians

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of science (*3–5*). Their main emphasis, however, has been on Darwin's forerunners, and on any and every trace of evolutionary thinking prior to 1859, or on the emergence of evolutionary concepts in Darwin's own thinking. These are legitimate approaches, but it seems to me that nothing brings out better the revolutionary nature of some of Darwin's concepts (*6*) than does an analysis of the arguments of contemporary anti-evolutionists.

Cuvier, Lyell, and Louis Agassiz, the leading opponents of organic evolution, were fully aware of many facts favoring an evolutionary interpretation, and likewise of the Lamarckian and other theories of transmutation. They devoted a great deal of energy to refute evolutionism (*7–10*) and supported instead what, to a modern student, would seem a less defensible position. What induced them to do so?

It is sometimes stated that they had no other legitimate choice, because—it is claimed—not enough evidence in favor of evolution was available before 1859. The facts refute this assertion. Lovejoy (*11*), in a superb analysis of this question, asks: "At what date can the evidence in favor of the theory of organic evolution . . . be said to have been fairly complete?" Here, one can perhaps distinguish two periods. During an earlier one, lasting from about 1745 to 1830, much became known that suggested evolution or, at least, a temporalized scale of perfection (*12*). Names like Maupertuis (1745), de Maillet (1749), Buffon (1749), Diderot (1769), Erasmus Darwin (1794), Lamarck (1809), and E. Geoffrey St. Hilaire (1818) characterize this period. Enough evidence from the fields of biogeography, systematics, paleontology, comparative anatomy, and animal and plant breeding, was already available by about 1812 (date of Cuvier's *Ossemens Fossiles*) to have made it possible to develop some of the arguments later made by Darwin in the *Origin of Species* (*6*). Soon afterward, however, much new evidence was produced by paleontology and stratigraphy, as well as by biogeography and comparative anatomy, with which only the evolutionary hypothesis was consistent; these new facts "reduced the rival hypothesis to a grotesque absurdity" (*11*). Yet, only a handful of authors [including Meckel (1821), Chambers (1844), Unger (1852), Schaaffhausen (1853), Wallace (1855)] adopted the concept of evolution while such leading authorities as Lyell, R. Owen, and Louis Agassiz vehemently opposed it.

Time does not permit me to marshal the abundant evidence in favor of evolution which existed by 1830. A comprehensive listing has been provided by Lovejoy (*11*), although the findings of systematics and biogeography must be added to his tabulation. The patterns of animal distribution were particularly decisive evidence, and it is no coincidence that Darwin devoted to it two entire chapters in the *Origin*. In spite of this massive evidence, creationism remained "the hypothesis tenaciously held by most men of science for at least twenty years before 1859" (*11*). It was not a lack of supporting facts, then, that prevented the acceptance of the theory of evolution, but rather the power of the opposing ideas.

Curiously, a number of nonscientists, particularly Robert Chambers (*13*) and Herbert Spencer saw the light well before the professionals. Chambers, the author of the *Vestiges of the Natural History of Creation*, developed quite a consistent and logical argument for evolutionism, and was instrumental in converting A. R. Wallace, R. W. Emerson, and A. Schopenhauer to evolutionism. As was the case with Diderot and Erasmus Darwin, these well-informed and broadly educated lay people looked at the problem in a "holistic" way, and thus perceived the truth more readily than did the professionals who were committed to certain well-established dogmas. A view from the distance is sometimes more revealing, for the understanding of broad issues, than the myopic scrutiny of the specialist.

Power of Retarding Concepts

Why were the professional geologists and biologists so blind when the manifestations of evolution were staring them in the face from all directions? Darwin's friend Hewett Watson put it this way in 1860 (*14*, p. 226): "How could Sir Lyell . . . for thirty years read, write, and think on the subject of species *and their succession*, and yet constantly look down the wrong road?" Indeed, how could he? And the same question can be asked for Louis Agassiz, Richard Owen, almost all of Lyell's geological colleagues, and all of Darwin's botanist friends from Joseph Hooker on down. They all displayed a nearly complete resistance to drawing what to us would seem to be the inevitable conclusion from the vast amount of evidence in favor of evolution.

Historians of science are familiar with this phenomenon; it happens almost invariably when new facts cast doubt on a generally accepted theory. The prevailing concepts, although more difficult to defend, have such a powerful hold over the thinking of all investigators, that they find it difficult, if not impossible, to free themselves of these ideas. To illustrate this by merely one example, I would like to quote a statement by Lyell: "It is idle . . . to dispute about the abstract possibility of the conversion of one species into another, when there are known causes, so much more active in their nature, which must always intervene and prevent the actual accomplishment of such conversions" (*9*, p. 162). Actually one searches in vain for a demonstration of such "known causes" and any proof that they "must" always intervene. The cogency of the argument relied entirely on the validity of silent assumptions.

In the particular case of the Darwinian revolution, what were the dominant ideas that formed roadblocks against the advance of evolutionary thinking? To name these concepts is by no means easy because they are silent assumptions, never fully articulated. When these assumptions rest on religious beliefs or on the acceptance of certain philosophies, they are particularly difficult to reconstruct. This is the major reason why there is so much difference of opinion in the interpretation of this period. Was theology responsible for the lag, or was it the authority of Cuvier or Lyell, or the acceptance of catastrophism (with progressionism), or the absence of a reasonable explanatory scheme? All of these interpretations and several others have been advanced, and all presumably played some role. Others, particularly the role of essentialism, have so far been rather neglected by the historians.

Natural Theology and Creationism

The period from 1800 to the middle of that century witnessed the greatest flowering of natural theology in Great Britain (*5, 15*). It was the age of Paley and the Bridgewater Treatises, and virtually all British scientists accepted the traditional Christian conception of a Creator God. The industrial revolution was in full swing, the poor workingman was exploited unmercifully, and the goodness and wisdom of the Creator was emphasized constantly to sooth guilty consciences. It became a moral obligation for the scientist to find additional proofs for the wisdom and constant attention of the Creator. When Chambers in his *Vestiges* (*13*) dared to replace direct intervention of the Creator by the action of secondary causes (natural laws), he was roundly condemned. Although the attacks were ostensibly directed against errors of fact, virtually all reviewers were horrified that Chambers had "annulled all distinction between physical and moral," and that he had degraded man by ranking him as a descendant of the apes and by interpreting the universe as "the progression and development of a rank, unbending, and degrading materialism" (*5*, p. 150; *16*). It is not surprising that in this intellectual climate Chambers had taken the precaution of publishing anonymously. Yet the modern reader finds little that is objectionable in Chambers' endeavor to replace supernatural explanations by scientific ones.

To a greater or lesser extent, all the scientists of that period resorted, in their explanatory schemes, to frequent interventions by the Creator (in the running of His world). Indeed, proofs of such interventions were considered the foremost evidence for His existence. Agassiz quite frankly describes the obligations of the naturalist in these words: "Our task is . . . complete as soon as we have proved His existence" (*10*, p. 132). To him the *Essay on Classification* was nothing but another Bridgewater Treatise in which the relationship of animals supplied a particularly elaborate and, for Agassiz, irrefutable demonstration of His existence.

Natural theology equally pervades Lyell's *Principles of Geology*. After discussing various remarkable instincts, such as pointing and retrieving, which are found in races of the dog, Lyell states: "When such remarkable habits appear in races of this species, we may reasonably conjecture that they were given with no other view than for the use of man and the preservation of the dog which thus obtains protection" (*9*, p. 455). Even though cultivated plants and domestic animals may have been created long before man, "some of the qualities of particular animals and plants may have been given solely with a view to the connection which, it was foreseen, would exist between them and man" (*9*, p. 456). Like Agassiz, Lyell believed that everything in nature is planned, designed, and has a predetermined end. "The St. Helena plants and insects [which are now dying out] may have lasted for their allotted term" (*9*, p. 9). The harmony of living nature and all the marvelous adaptations of animals and plants to each other and to their environment seemed to him thus fully and satisfactorily explained.

Creationism and the Advances of Geological Science

At the beginning of the 18th century, the concept of a created world seemed internally consistent as long as this world was considered only recently created (in 4004 B.C.), static, and unchanging. The "ladder of perfection" (part of God's plan) accounted for the "higher" and "lower" organization of animals and man, and Noah's flood for the existence of fossils. All this could be readily accommodated within the framework of a literal Biblical interpretation.

The discovery of the great age of the earth (*5*, *17*) and of an ever-increasing number of distinct fossil faunas in different geological strata necessitated abandoning the idea of a single creation. Repeated creations had to be postulated, and the necessary number of such interventions had to be constantly revised upward. Agassiz was willing to accept 50 or 80 total extinctions of life and an equal number of new creations. Paradoxically, the advance of scientific knowledge necessitated an increasing recourse to the supernatural for explanation. Even such a sober and cautious person as Charles Lyell frequently explained natural phenomena as due to "creation" and, of course, a carefully thought-out creation. The fact that the brain of the human embryo successively passes through stages resembling the brains of fish, reptile, and lower mammal discloses "in a highly interesting manner, the unity of plan that runs through the organization of the whole series of vertebrated animals; but they lend no support whatever to the notion of a gradual transmutation of one species into another; least of all of the passage, in the course of many generations, from an animal of a more simple to one of a more complex structure" (*9*, p. 20). When a species becomes extinct it is replaced "by new creations" (*9*, p. 45). Nothing is impossible in creation. "Creation seems to require omnipotence, therefore we cannot estimate it" (*18*, p. 4). "Each species may have had its origin in a single pair, or individual where an individual was sufficient, and species may have been created in succession at such times and in such places as to enable them to multiply and endure for an *appointed* period, and occupy an *appointed* space of the globe?" (italics mine) (*9*, pp. 99–100). Everything is done according to plan. Since species are fixed and unchangeable, everything about them, such as the area of distribution, the ecological context, adaptations to cope with competitors and enemies, and even the date of extinction, was previously "appointed," that is, predetermined.

This constant appeal to the supernatural amounted to a denial of all sound scientific methods, and to the adoption of explanations that could neither be proven nor refuted. Chambers saw this quite clearly (*13*). When there is a choice between two theories, either special creation or the operation of general laws instituted by the Creator, he exclaimed, "I would say that the latter [theory] is greatly preferable, as it implies a far grander view of the Divine power and dignity than the other" (*13*, p. 117). Indeed, the increasing knowledge of geological sequences, and of the facts of comparative anatomy and geographic distribution, made the picture of special creation more ludicrous every day (*11*, p. 413).

Essentialism and a Static World

Thus, theological considerations clearly played a large role in the resistance to the adoption of evolutionary views in England (and also in France). Equally influential, or perhaps even more so, was a philosophical concept. Philosophy and natural history during the first half of the 19th century, particularly in continental Europe, were strongly dominated by typological thinking [designated "essentialism" by Popper (*19*, *20*)]. This presumes that the changeable world of appearances is based on underlying immutable essences, and that all members of a class represent the same essence. This idea was first clearly enunciated in Plato's concept of the *eidos*. Later it became a dominant element in the teachings of Thomism (*21*), and of all idealistic philosophy. The enormous role of essentialism in retarding the acceptance of evolutionism was long overlooked (*22, 23*). The observed vast variability of the world has no more reality, according to this philosophy, than the shadows of an object on a cave wall, as Plato expressed it in his allegory. The only things that are permanent, real, and sharply discontinuous from each other are the fixed, unchangeable "ideas" underlying the observed variability. Discontinuity and fixity are, according to the essentialist, as much the properties of the living as of the inanimate world.

As Reiser (*24*) has said, a belief in discontinuous, immutable essences is incompatible with a belief in evolution. Agassiz was an extreme representative of this philosophy (*23*). To a lesser extent the same can be demonstrated for all of the other opponents of evolutionism, including Lyell. When rejecting Lamarck's claim that species and genera intergrade with each other, Lyell proposes that the following laws "prevail in the economy of the animate creation. . . . Thirdly, that there are fixed limits beyond which the descendants from common parents can never deviate from a certain type; fourthly, that each species springs from one original stock, and can never be permanently confounded by intermixing with the progeny of any other stock; fifthly, that each species shall endure for a considerable period of time" (*9*, p. 433). All nature consists, according to Lyell, of fixed types created at a definite time. To him these types were morphological entities, and he was rather shocked by Lamarck's idea that changes in behavior could have any effect on morphology.

As an essentialist, Lyell showed no understanding of the nature of genetic variation. Strictly in the scholastic tradition, he believed implicitly that essential characters could not change; this could occur only with nonessential characters. If an animal is brought into a new environment, "a short period of time is generally sufficient to effect nearly the whole change which an alteration of external circumstances can bring about in the habits of a species, . . . such capacity of accommodation to new circumstances is enjoyed in very different degrees by different species" (*9*, p. 464). For instance, if we look at the races of dogs, they show many superficial differences "but, if we look for some of those essential changes which would be required to lend even the semblance of a foundation for the theory of Lamarck, respecting the growth of new organs and the gradual obliteration of others, we find nothing of the kind" (*9*, p. 438). This forces Lyell to question even Lamarck's conjecture "that the wolf may have been the original of the dog." The fact that in the (geologically speaking) incredibly short time since the dog was domesticated, such drastically different races as the Eskimo dog, the hairless Chihuahua, the greyhound, and other extremes evolved is glossed over.

Lyell's Species Concept

Holding a species concept that allowed for no essential variation, Lyell credited species with little plasticity and adaptability. This led him to an interpretation of the fossil record that is very different from that of Lamarck. Anyone studying the continuous changes in the earth's surface, states Lyell, "will immediately perceive that, amidst the vicissitudes of the earth's surface, species cannot be immortal, but must perish, one after the other, like the individuals which compose them. There is no possibility of escaping from this conclusion, without resorting to some hypothesis as violent as that of Lamarck who imagined . . . that species are each of them endowed with indefinite powers of modifying their organization, in conformity to the endless changes of circumstances to which they are exposed" (*9*, pp. 155–156).

The concept of a steady extermination of species and their replacement by newly created ones, as proposed by Lyell, comes close to being a kind of microcatastrophism, as far as organic nature is concerned. Lyell differed from Cuvier merely in pulverizing the catastrophes into events relating to single species, rather than to entire faunas. In the truly decisive point, the rejection of any possible continuity between species in progressive time sequences, Lyell entirely agreed with Cuvier. When he traced the history of a species backward, Lyell inexorably arrived at an original ancestral pair, at the original center of creation. There is a total absence in his arguments of any thinking in terms of populations.

The enormous power of essentialism is in part explainable by the fact that it fitted the tenets of creationism so well; the two dogmas strongly reinforced each other. Nothing in Lyell's geological experience seriously contradicted his essentialism. It was not shaken until nearly 25 years later when Lyell visited the Canary Islands (from December 1853 to March 1854) and became acquainted with the same kind of phenomena that, in the Galapagos, had made Darwin an evolutionist and which, in the East Indian Archipelago, gave concrete form to the incipient evolutionism of A. R. Wallace. Wilson (*18*) has portrayed the growth of doubt which led Lyell to publicly confess his conversion to evolutionism in 1862. The adoption of population thinking by him was a slow process, and even years after his memorable discussion with Darwin (16 April 1856), Lyell spoke in his notebooks of "variation *or* selection" as the important factor in evolution in spite of the fact that Darwin's entire argument was founded on the need for *both* factors as the basis of a satisfactory theory.

Lyell and Uniformitarianism

It is a long-standing tradition in biological historiography that Lyell's revival of Hutton's theory of uniformitarianism was a major factor in the eventual adoption of evolutionary thinking. This thesis seems to be a great oversimplification; it is worthwhile to look at the argument a little more critically (*25*). When the discovery of a series of different fossil faunas, separated by unconformities, made the story of a single flood totally inadequate, Cuvier and others drew the completely correct conclusion that these faunas, particularly the alternation of marine and terrestrial faunas, demonstrated a frequent alternation of rises of the sea above the land and the subsequent reemergence of land above the sea. The discovery of mammoths frozen into the ice of Siberia favored the additional thesis that such changes could happen very rapidly. Cuvier was exceedingly cautious in his formulation of the nature of these "revolutions" and "catastrophes," but he did admit, "The breaking to pieces and overturning of the strata, which happened in former catastrophes, show plainly enough that they were sudden and violent like the last [which killed the mammoths and embedded them in ice]" (*26*, p. 16). He implied that most of these events were local rather than universal phenomena, and he did not maintain that a new creation had been required to produce the species existing today. He said merely "that they [modern species] did not anciently occupy their present locations and that they must have come there from elsewhere" (*26*, pp. 125–126).

Cuvier's successors did not maintain his caution. The school of the so-called progressionists (*27*) postulated that each fauna was totally exterminated by a catastrophe at the end of each geologic period, followed by the special creation of an entirely new organic world. Progressionism, therefore, was intellectually a backward step from the widespread 18th-century belief that the running of the universe required only occasional, but definitely not incessant, active intervention by the Creator: He maintained stability largely through the laws that He had decreed at the beginning, and which allowed for certain planetary and other perturbations. This same reasoning could have easily been applied to the organic world, and this indeed is what was done by Chambers in 1844, and by many other devout Christians after 1859.

Catastrophism was not as great an obstacle to evolutionism as often claimed. It admitted, indeed it emphasized, the advance which each new creation showed over the preceding one. By also conceding that there had been 30, 50, or even more than 100 extinctions and new creations, it made the concept of these destructions increasingly absurd, and what was finally left, after the absurd destructions had been abandoned, was the story of the constant progression of faunas (*28*). As soon as one rejected reliance on supernatural forces, this progression automatically became evidence in favor of evolution. The only other assumption one had to make was that many of the catastrophes and extinctions had been localized events. This was, perhaps, not too far from Cuvier's original viewpoint.

The reason why catastrophism was adopted by virtually all of the truly productive leading geologists in the first half of the 19th century is that the facts seemed to support it. Breaks in fossil strata, the occurrence of vast lava flows, a replacement of terrestrial deposits by marine ones and the reverse, and many other phenomena of a similar, reasonably violent nature (including the turning upside down of whole fossil sequences) all rather decisively refuted a rigid uniformitarian interpretation. This is why Cuvier, Sedgwick, Buckland, Murchison, Conybeare, Agassiz, and de Beaumont, to mention a few prominent geologists, adopted more or less catastrophist interpretations.

Charles Lyell was the implacable foe of the "catastrophists," as his opponents were designated by Whewell (*29*). In his *Principles of Geology* (*9*), Lyell promoted a "steady state" concept of the world, best characterized by Hutton's motto, "no vestige of a beginning—no prospect of an end." Whewell coined the term "uniformitarianism" (*30*) for this school of thought, a term which unfortunately had many different meanings. The most important meaning was that it postulated that no forces had been active in the past history of the earth that are not also working today. Yet, even this would permit two rather different interpretations. Even if one includes supernatural agencies among forces and causes, one can still be a consistent uniformitarian, provided one postulates that the Creator continues to reshape the world actively even at the present. Rather candidly, Lyell refers to this interpretation, accepted by him, as "the perpetual intervention hypothesis" (*18*, p. 89).

Almost diametrically opposed to this were the conclusions of those who excluded all recourse to supernatural interventions. Uniformitarianism to them meant simply the consistent application of natural laws not only to inanimate nature (as was done by Lyell) but also to the living world (as proposed by Chambers). The important component in their argument was the rejection of supernatural intervention rather than a lip service to the word uniformity.

It is important to remember that Lyell applied his uniformitarianism in a consistent manner only to inanimate nature, but left the door open for special creation in the living world. Indeed, as Lovejoy (*11*) states justly, when it came to the origin of new species, Lyell, the great champion of uniformitarianism, embraced "the one doctrine with which uniformitarianism was wholly incompatible—the theory of numerous and discontinuous miraculous special creations." Lyell himself did not see it that way. As he wrote to Herschel (*31*), he considered his notion "of a succession of extinction of species, and creation of new ones, going on perpetually now . . . the grandest which I had ever conceived, so far as regards the attributes of the Presiding Mind." There is evidence, however, that Lyell considered these creations not always as miracles, but sometimes as occurring "through the intervention of intermediate causes" thus being "a natural, in contradistinction to a miraculous process." By July 1856, after having read Wallace's 1855 paper, and after having discussed evolution with Darwin (16 April 1856), Lyell had become completely converted to believing that the introduction of new species was "governed by laws in the same sense as the Universe is governed by laws" (*18*, p. 123).

Only the steady-state concept of uniformitarianism was novel in Lyell's interpretation. The insistence that nature operates according to eternal laws, with the same forces acting at all times was, from Aristotle on, the standard explanation among most of those who did not postulate a totally static world, for instance, among the French naturalists preceding Cuvier. Consequently, acceptance of uniformitarianism did not, as Lyell himself clearly demonstrated, require the acceptance of evolutionism. If one believed in a steady-state world, as did Lyell, uniformitarianism was incompatible with evolution. Only if it was combined with the concept of a steadily changing world, as it was in Lamarck's thinking, did it encourage a belief in evolution. It is obvious, then, that the statement "uniformitarianism is the pacemaker of evolutionism," is an exaggeration, if not a myth.

But what effect did Lyell have on Darwin? Everyone agrees that it was profound; there was no other person whom Darwin admired as greatly as Lyell. *Principles of Geology*, by Lyell, was Darwin's favorite reading on the *Beagle* and gave his geological interests new direction. After the return of the *Beagle* to England, Darwin received more stimulation and encouragement from Lyell than from any other of his friends. Indeed, Lyell became a father figure for him and stayed so for the rest of his life. Darwin's whole way of writing, particularly in the *Origin of Species*, was modeled after the *Principles*. There is no dispute over these facts.

But, what was Lyell's impact on Darwin's evolutionary ideas? There is much to indicate that the influence was largely negative. Knowing how firmly Lyell was opposed to the possibility of a transmutation of species, as documented by his devastating critique of Lamarck, Darwin was very careful in what he revealed to Lyell. He admitted that he doubted the fixity of species, but after that the two friends apparently avoided a further discussion of the subject. Darwin was far more outspoken with Hooker to whom he confessed as early as January 1844, "I am almost convinced . . . that species are not (it is like confessing murder) immutable" (*14*, p. 23). It was not until 1856 that Darwin fully outlined his theory of evolution to Lyell (*18*, p. xlix). This reticence of Darwin was not due to any intolerance on Lyell's part (or else Lyell would not have, after 1856, encouraged Darwin so actively to publish his heretical views), but rather to an unconscious fear on Darwin's part that his case was not sufficiently persuasive to convert such a formidable opponent as Lyell. There has been much speculation as to why Darwin had been so tardy about publishing his evolutionary views. Several factors were involved (one being the reception of the *Vestiges*), but I am rather convinced that his awe of Lyell's opposition to the transmutation of species was a much more weighty reason than has been hitherto admitted. It is no coincidence that Darwin finally began to write his great work within 3 months after Lyell took the initiative to consult him and to encourage him. Lovejoy summarizes the effect of Lyell's opposition to evolution in these words: "It was . . . his example and influence, more than the logical force of his arguments, that so long helped to sustain the prevalent belief that transformism was not a scientifically respectable theory" (*11*). I entirely agree with this evaluation.

Unsuccessful Refutations Owing to Wrong Choice of Alternatives

Creationism, essentialism, and Lyell's authority were not, however, the only reasons for the delay in the acceptance of evolution; others were important weaknesses in the scientific methodology of the period. There was still a demand for conclusive proofs. "Show me the breed of dogs with an entirely new organ," Lyell seems to say, "and I will believe in evolution." That much of science consists merely in showing that one interpretation is more probable than another one, or consistent with more facts than another one, was far less realized at that period than it is now (*32*).

That victory over one's opponent consists in the refutation of his arguments, however, was taken for granted. Cuvier's, Lyell's, Agassiz's, and Darwin's detailed argumentations were all attempts to "falsify," as Popper (*33*) has called it, the statements of their opponents. This method, however, has a number of weaknesses. For instance, it is often quite uncertain what kind of evidence or argument truly represents a falsification. More fatal is the frequently made assumption that there are only two alternatives in a dispute. Indeed, the whole concept of "alternative" is rather ambiguous, as I shall try to illustrate with some examples from pre-Darwinian controversies.

We can find numerous illustrations in the antievolutionary writings of Charles Lyell and Louis Agassiz of the limitation to only two alternatives when actually there was at least a third possible choice. Louis Agassiz, for instance, never seriously considered the possibility of true evolution, that is, of descent with modification. For him the world was either planned by the Creator, or was the accidental product of blind physical causes (in which case evolution would be the concatenation of such accidents). He reiterates this singularly simple-minded choice throughout the *Essay on Classification* (*10*): "physical laws" versus "plan of creation" (p. 10), "spontaneous generation" versus "divine plan" (p. 36), "physical agents" versus "plan ordained from the beginning" (p. 37), "physical causes" versus "supreme intellect" (p. 64), and "physical causes" versus "reflective mind" (p. 127). By this choice he not only excluded the possibility of evolution as envisioned by Darwin, but even as postulated by Lamarck. Nowhere does Agassiz attempt to refute Lamarckian evolution. His physical causes, in turn, are an exceedingly narrow definition of natural causes, since it is fully apparent that Agassiz had a very simple-minded Cartesian conception of physical causes as motions and mechanical forces. "I am at a loss to conceive how the origin of parasites can be ascribed to physical causes" (*10*, p. 126). "How can physical causes be responsible for the form of animals when so many totally different animal types live in the same area subjected to identical physical causes?" (*10*, pp. 13–14). The abundant regularities in nature demonstrate "the plan of a Divine Intelligence" since they cannot be the result of blind physical forces. (This indeed was a standard argument among adherents of natural theology.) It never occurred to Agassiz that none of his arguments excluded a third possibility, the gradual evolution of these regularities by processes that can be daily observed in nature. This is why the publication of Darwin's *Origin* was such a shock to him. The entire evidence against evolution, which Agassiz had marshaled so assiduously in his *Essay on Classification*, had become irrelevant. He had failed completely to provide arguments against a third possibility, the one advanced by Darwin.

The concept of evolution, at that period, still evoked in most naturalists the image of the *scala naturae*, the ladder of perfection. No one was more opposed to this concept than Lyell, the champion of a steady-state world. Any finding that contradicted a steady progression from the simple toward the more perfect refuted the validity of evolution, he thought. Indeed, the fact that mammals appeared in the fossil record before birds, and that primates appeared in the Eocene considerably earlier than some of the orders of "lower" mammals were, to him, as decisive a refutation of the evolutionary theory as was to Agassiz the fact that the four great types of animals appeared simultaneously in the earliest fossil-bearing strata.

The assumption that refuting the *scala naturae* would refute once and for all any evolutionary theory is another illustration of insufficient alternatives. Lyell was quite convinced that the concept of a steady-state world would be validated (including regular special creations), if it could be shown that those mechanisms were improbable or impossible which Lamarck had proposed to account for evolutionary change.

But there were also other violations of sound scientific method; for instance, the failure to see that both of two alternatives might be valid. In these cases, the pre-Darwinians arrived at erroneous conclusions because they were convinced that they had to make a choice between two processes which, in reality, occur simultaneously. For example, neither Lamarck nor Lyell understood speciation (the multiplication of species), but this failure led them to opposite conclusions. When looking at fossil faunas, Lamarck, a great believer in the adaptability of natural species, concluded that all the contained species must have evolved into very different descendants. Lyell, as an essentialist, rejected the possibility of a change in species and therefore he believed, like Cuvier, that all of the species had become extinct, with replacements provided by special creation. Neither Lamarck nor Lyell imagined that both processes, speciation and extinction, could occur simultaneously. That the turnover of faunas could be a balance of both processes never entered their minds.

Failure to Separate Distinct Phenomena

A third type of violation of scientific logic was particularly harmful to the acceptance of evolutionary thinking. This was the erroneous assumption that certain characteristics are inseparably combined. For instance, both Linnaeus and Darwin assumed, as I pointed out at an earlier occasion (*34*), that if one admitted the *reality* of species in nature, one would also have to postulate their immutable *fixity*. Lyell, as a good essentialist, unhesitatingly endorsed the same thesis: "From the above considerations, it appears that species have a real existence in nature; and that each was endowed, at the time of its creation, with the attributes and organization by which it is now distinguished" (*9*, p. 21). He is even more specific about this in his notebooks (*18*, p. 92). That species could have full "reality" in the nondimensional situation (*34*) and yet evolve continuously was unthinkable to him. Reality and constancy of species were to him inseparable attributes.

Impact of the Origin of Species

The situation changed drastically and permanently with the publication of the *Origin of Species* in 1859. Darwin marshaled the evidence in favor of a transmutation of species so skillfully that from that point on the eventual acceptance of evolutionism was no longer in question. But he did more than that. In natural selection he proposed a mechanism that was far less vulnerable than any other previously proposed. The result was an entirely different concept of evolution. Instead of endorsing the 18th-century concept of a drive toward perfection, Darwin merely postulated change. He saw quite clearly that each species is forever being buffeted around by the capriciousness of the constantly changing environment. "Never use the word(s) higher and lower" (*35*) Darwin reminded himself. By chance this process of adaptation sometimes results in changes that can be interpreted as progress, but there is no intrinsic mechanism generating inevitable advance.

Virtually all the arguments of Cuvier, Lyell, and the progressionists became irrelevant overnight. Essentialism had been the major stumbling block, and the development of a new concept of species was the way to overcome this obstacle. Lyell himself eventually (after 1856) understood that the species problem was the crux of the whole problem of evolution, and that its solution had potentially the most far-reaching consequences: "The ordinary naturalist is not sufficiently aware that, when dogmatizing on what species are, he is grappling with the whole question of the organic world and its connection with a time past and with man" (*18*, p. 1). And, since he came to this conclusion after studying speciation in the Canary Islands, he added: "A group of islands, therefore, is the fittest place for Nature's trial of such permanent variety-making and where the problem of species-making may best be solved" (*18*, p. 93). This is what Darwin had discovered 20 years earlier.

Special Aspects of the Darwinian Revolution

No matter how one defines a scientific revolution, the Darwinian revolution of 1859 will have to be included. Who would want to question that, by destroying the anthropocentric concept of the universe, it caused a greater upheaval in man's thinking than any other scientific advance since the rebirth of science in the Renaissance? And yet, in other ways, it does not fit at all the picture of a revolution. Or else, how could H. J. Muller have exclaimed as late as 1959: "One hundred years without Darwinism are enough!" (*36*)? And how could books such as Barzun's *Darwin, Marx, Wagner* (1941) and Himmelfarb's *Darwin and the Darwinian Revolution* (1959), both displaying an abyss of ignorance and misunderstanding, have been published relatively recently? Why has this revolution in some ways made such extraordinarily slow headway?

A scientific revolution is supposedly characterized by the replacement of an old explanatory model by an incompatible new one (*1*). In the case of the theory of evolution, the concept of an instantaneously created world was replaced by that of a slowly evolving world, with man being part of the evolutionary stream. Why did the full acceptance of the new explanation take so long? The reason is that this short description is incomplete, and therefore misleading, as far as the Darwinian revolution is concerned.

Before analyzing this more fully, the question of the date of the Darwinian revolution must be raised. That the year 1859 was a crucial one in its history is not questioned. Yet, this still leaves a great deal of leeway to interpretation. On one hand, one might assert that the age of evolutionism started even before Buffon, and that the publication of the *Origin* in 1859 was merely the last straw that broke the camel's back. On the other hand, one might go to the opposite extreme, and claim that not much had changed in the thinking of naturalists between the time of Ray and Tournefort and the year 1858, and that the publication of the *Origin* signified a drastic, almost violent revolution. The truth is somewhere near the middle; although there was a steady, and ever-increasing, groundswell of evolutionary ideas since the beginning of the 18th century, Darwin added so many new ideas (particularly an acceptable mechanism) that the year 1859 surely deserves the special attention it has received. Two components of the Darwinian revolution must thus be distinguished: the slow accumulation of evolutionary facts and theories since early in the 18th century, and the decisive contribution which Darwin made in 1859. Together these two components constitute the Darwinian revolution.

The long time span is due to the fact that not simply the acceptance of one new theory was involved, as in some other scientific revolutions, but of an entirely new conceptual world, consisting of numerous separate concepts and beliefs (*37*). And not only were scientific theories involved, but also a whole set of metascientific credos. Let me prove my point by specifying the complex nature of the revolution: I distinguish six major elements in this revolution, but it is probable that additional ones should be recognized (*32*).

The first three elements concern scientific replacements:

1) *Age of the earth.* The revolution began when it became obvious that the earth was very ancient rather than having been created only 6000 years ago (*17*). This finding was the snowball that started the whole avalanche.

2) *Refutation of both catastrophism (progressionism) and of a steady-state world.* The evolutionists, from Lamarck on, had claimed that the concept of a more or less steadily evolving world, was in better agreement with the facts than either the catastrophism of the progressionists or Lyell's particular version of a steady-state world. Darwin helped this contention of the evolutionists to its final victory.

3) *Refutation of the concept of an automatic upward evolution.* Every evolutionist before Darwin had taken it for granted that there was a steady progress of perfection in the living world. This belief was a straight-line continuation of the (static) concept of a scale of perfection, which was maintained even by the progressionists for whom each new creation represented a further advance in the plan of the Creator.

Darwin's conclusion, to some extent anticipated by Lamarck, was that evolutionary change through adaptation and specialization by no means necessitated continuous betterment. This view proved very unpopular, and is even today largely ignored by nonbiologists. This neglect is well illustrated by the teachings of the school of evolutionary anthropology, or those of Bergson and Teilhard de Chardin.

The last three elements concern metascientific consequences. The main reason why evolutionism, particularly in its Darwinian form, made such slow progress is that it was the replacement of one entire *weltanschauung* by a different one. This involved religion, philosophy, and humanism.

4) *The rejection of creationism.* Every antievolutionist prior to 1859 allowed for the intermittent, if not constant, interference by the Creator. The natural causes postulated by the evolutionists completely separated God from his creation, for all practical purposes. The new explanatory model replaced planned teleology by the haphazard process of natural selection. This required a new concept of God and a new basis for religion.

5) *The replacement of essentialism and nominalism by population thinking.* None of Darwin's new ideas was quite so revolutionary as the replacement of essentialism by population thinking (*19–23, 38*). It was this concept that made the introduction of natural selection possible. Because it is such a novel concept, its acceptance has been slow, particularly on the European continent and outside biology. Indeed, even today it has by no means universally replaced essentialism.

6) *The abolition of anthropocentrism.* Making man part of the evolutionary stream was particularly distasteful to the Victorians, and is still distasteful to many people.

Nature of the Darwinian Revolution

It is now clear why the Darwinian revolution is so different from all other scientific revolutions. It required not merely the replacement of one scientific theory by a new one, but, in fact, the rejection of at least six widely held basic beliefs [together with some methodological innovations (*32*)].

Furthermore, it had a far greater relevance outside of science than any of the revolutions in the physical sciences. Einstein's theory of relativity, or Heisenberg's of statistical prediction, could hardly have had any effect on anybody's personal beliefs. The Copernican revolution and Newton's world view required some revision of traditional beliefs. None of these physical theories, however, raised as many new questions concerning religion and ethics as did Darwin's theory of evolution through natural selection.

In a way, the publication of the *Origin* in 1859 was the midpoint of the so-called Darwinian revolution rather than its beginning. Stirrings of evolutionary thinking preceded the *Origin* by more than 100 years, reaching an earlier peak in Lamarck's *Philosophie Zoologique* in 1809. The final breakthrough in 1859 was the climax in a long process of erosion, which was not fully completed until 1883 when Weismann rejected the possibility of an inheritance of acquired characters.

As in any scientific revolution, some of the older opponents, such as Agassiz, never became converted. But the Darwinian revolution differed by the large number of workers who accepted only part of the package. Many zoologists, botanists, and paleontologists eventually accepted gradual evolution through natural causes, but not through natural selection. Indeed, on a worldwide basis, those who continued to reject natural selection as the prime cause of evolutionary change were probably well in the majority until the 1930's.

Two conclusions emerge from this analysis. First, the Darwinian and quite likely other scientific revolutions consist of the replacement of a considerable number of concepts. This requires a lengthy period of time, since the new concepts will not all be proposed simultaneously. Second, the mere summation of new concepts is not enough; it is their constellation that counts. Uniformitarianism, when combined with the belief in a static essentialistic world, leads to the steady-state concept of Lyell, while when combined with a concept of change, it leads to the evolutionism of Lamarck. The observation of evolutionary changes, combined with essentialist thinking, leads to various saltationist or progressionist theories, but, combined with population thinking, it leads to Darwin's theory of evolution by natural selection.

It is now evident that the Darwinian revolution does not conform to the simple model of a scientific revolution, as described, for instance, by T. S. Kuhn (*1*). It is actually a complex movement that started nearly 250 years ago; its many major components were proposed at different times, and became victorious independently of each other. Even though a revolutionary climax occurred unquestionably in 1859, the gradual acceptance of evolutionism, with all of its ramifications, covered a period of nearly 250 years (*37*).

References and Notes

1. T. S. Kuhn, *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago, 1962).
2. S. Toulmin, *Boston Stud. Phil. Sci.* **3**, 333 (1966); I. Lakatos and A. Musgrave, Eds., *Criticism and the Growth of Knowledge* (Cambridge Univ. Press, Cambridge, England, 1970), reviewed by D. Shapere, *Science* **172**, 706 (1971).
3. To cite only a few: L. Eiseley, *Darwin's Century* (Doubleday, New York, 1958); B. Glass, O. Temkin, W. L. Straus, Jr., Eds., *Forerunners of Darwin, 1745–1859* (Johns Hopkins Press, Baltimore, 1959); J. C. Greene, *The Death of Adam* (Iowa State Univ. Press, Ames, 1959); W. Zimmermann, *Evolution, Geschichte ihrer Probleme und Erkenntnisse* (Alber, Freiburg, West Germany, 1953); J. C. Greene, "The Kuhnian paradigm and the Darwinian revolution in natural history," in *Perspectives in the History of Science and Technology*, D. H. D. Roller, Ed. (Univ. of Oklahoma Press, Norman, 1971); M. T. Ghiselin, *New Lit. Hist.* **3**, 113 (1971).
4. G. de Beer, *Charles Darwin* (Doubleday, Garden City, N.Y., 1964).
5. C. C. Gillispie, *Genesis and Geology* (Harvard Univ. Press, Cambridge, Mass., 1951; rev. ed., Harper & Row, New York, 1959).
6. C. Darwin, *On the Origin of Species by Means of Natural Selection* (1859).
7. G. Cuvier, *Essay on the Theory of the Earth* (Edinburgh, ed. 3, 1817); much of it is an implicit refutation of Lamarck's ideas.
8. W. Coleman, *Georges Cuvier, Zoologist* (Harvard Univ. Press, Cambridge, Mass., 1964).
9. C. Lyell, *Principles of Geology* (John Murray,

London, 1835), vols. 2 and 3 (I have used ed. 4). Important for British biology because it was the first presentation of Lamarck's theories to the English-speaking world (Book III, chap. I–XI). Darwin had previously heard about Lamarck from R. E. Grant in Edinburgh in 1827 [see (*4*, p. 28)].

10. L. Agassiz, *Essay on Classification* (Little, Brown, Boston, 1857; reprint, Belknap, Cambridge, Mass., 1962).
11. A. O. Lovejoy, "The argument for organic evolution before the *Origin of Species*, 1830–1858," in *Forerunners of Darwin, 1745–1859*, B. Glass, O. Temkin, W. L. Straus, Jr., Eds. (Johns Hopkins Press, Baltimore, 1959), pp. 356–414.
12. A. O. Lovejoy, *The Great Chain of Being* (Harvard Univ. Press, Cambridge, Mass., 1963), Lecture 9.
13. The authorship of the anonymously published *Vestiges of the Natural History of Creation* (1844) did not become known until after the death of Robert Chambers [M. Millhauser, *Just Before Darwin* (Wesleyan Univ. Press, Middletown, Conn., 1959); see also (*5*, chap. 6)]. A sympathetic analysis of the *Vestiges*, that does not concentrate on Chambers' errors and his gullibility, is still wanting [F. N. Egerton, *Stud. Hist. Phil. Sci.* **1**, 176 (1971)].
14. F. Darwin, Ed., *Life and Letters of Charles Darwin* (Sources of Science Ser. No. 102; reprint of 1888 ed., Johnson Reprints, New York, 1969), vol. 2.
15. H. Fruchtbaum, "Natural theology and the rise of science," thesis, Harvard University (1964).
16. A. Sedgwick, *Edinburgh Rev.* **82**, 3 (1845).
17. F. C. Haber, in *Forerunners of Darwin, 1745–1859*, B. Glass, O. Temkin, W. L. Straus, Jr., Eds. (Johns Hopkins Press, Baltimore, 1959), pp. 222–261.
18. L. G. Wilson, Ed., *Sir Charles Lyell's Scientific Journals on the Species Question* (Yale Univ. Press, New Haven, Conn., 1970).
19. K. R. Popper, *The Open Society and its Enemies* (Routledge & Kegan Paul, London, 1945).
20. D. Hull, *Brit. J. Phil. Sci.* **15**, 314 (19 *ibid.* **16**, 1 (1965).
21. Aristotle is traditionally included among the essentialists, but newer researches cast considerable doubt on this. There is a growing suspicion that much of the late medieval thought labeled as Aristotelianism, had little to do with Aristotle's actual thinking. See, for instance, M. Delbrück, in *Of Microbes and Life*, J. Monod and E. Borek, Eds. (Columbia Univ. Press, New York, 1971), pp. 50–55.
22. E. Mayr, in *Evolution and Anthropology: A Centennial Appraisal* (Anthropological Society of Washington, Washington, D.C., 1959).
23. ———, *Harvard Libr. Bull.* **13**, 165 (1959).
24. O. L. Reiser, in *A Book that Shook the World*, R. Buchsbaum, Ed. (Univ. of Pittsburgh Press, Pittsburgh, Pa., 1958).
25. It is impossible in the limited space available to give a full documentation for the refutation of this thesis [see W. Coleman, *Biology in the Nineteenth Century* (Wiley, New York, 1971), p. 63].
26. G. Cuvier, *Essay on the Theory of the Earth*, R. Jameson, Transl. (Edinburgh, ed. 3, 1817). It is frequently stated that Cuvier believed in large-scale creations, necessary to repopulate the globe after major catastrophes, and this may well be true. However, I have been unable to find an unequivocal statement to this effect in Cuvier's writings [see also (*8*, p. 136)].
27. Progressionism was the curious theory according to which evolution did not take place in the organisms but rather in the mind of the Creator, who—after each catastrophic extinction—created a new fauna in the more advanced state to which His plan of creation had progressed in the meantime. This thought was promoted in Britain particularly by Hugh Miller (*Footprints*, 1847), Sedgwick (*Discourse*, 1850), and Murchison (*Siluria*, 1854), and in America by L. Agassiz (*Essay*, 1857); see (*3*).
28. The difference between catastrophism and uniformitarianism became smaller, as it was realized that many of the "catastrophes" had been rather minor events, and that contemporary geological phenomena (earthquakes, volcanic eruptions, tidal waves, glaciation) could have rather catastrophic effects [S. Toulmin, in *Criticism and the Growth of Knowledge*, I. Lakatos and A. Musgrave, Eds. (Cambridge Univ. Press, Cambridge, England, 1970), p. 42].
29. [W. Whewell] *Brit. Critic* **9**, 180 (1831); *Quart. Rev.* **47**, 103 (1832). For a full discussion of catastrophism see (*5*). A new interpretation of the traditional geological theories which Lyell opposed is given by M. J. S. Rudwick, "Uniformity and progression," in *Perspectives in the History of Science and Technology*, D. H. D. Roller, Ed. (Univ. of Oklahoma Press, Norman, 1971), pp. 209–237.
30. The term uniformitarianism was applied to at least four different concepts, and this caused considerable confusion, to put it mildly. For recent reviews see R. Hooykaas, *Natural Law and Divine Miracle* (E. J. Brill, Leiden, the Netherlands, 1959); S. J. Gould, *Amer. J. Sci.* **263**, 223 (1965); C. C. Albritton, Jr., Ed., "Uniformity and simplicity," *Geol. Soc. Amer. Spec. Pap. No. 89* (19 M. S. J. Rudwick, *Proc. Amer. Phil. Soc.* **111**, 272 (1967); G. G. Simpson, "Uniformitarianism," in *Essays in Evolution and Genetics* (Appleton-Century-Crofts, New York, 1970), pp. 43–96. The most important interpretations of uniformitarianism are: the same processes act now as in the past, the magnitude of geological events is as great now as in the past, and the earth a steady-state system.
31. Mrs. Lyell, Ed., *Life, Letters and Journals of Sir Charles Lyell* (John Murray, London, 1881), vol. 1, pp. 467–469 (letter of 1 June 1836 to J. W. Herschel).
32. Darwin's *Origin* was one of the first scientific treatises in which the hypothetico-deductive method was rather consistently employed [M. Ghiselin, *The Triumph of the Darwinian Method* (Univ. of California Press, Berkeley, 1969)]. Equally important, and even more novel, was Darwin's demonstration that deterministic prediction is not a necessary component of causality [M. Scriven, *Science* **130**, 477 (1959)]. Perhaps this can be considered a corollary of population thinking, but it is further evidence for the extraordinary complexity of the Darwinian revolution.
33. K. R. Popper, *The Logic of Scientific Discovery* (Hutchison, London, 1959).
34. E. Mayr, Ed., *The Species Problem* (AAAS, Washington, D.C., 1957), p. 2.
35. F. Darwin and A. C. Seward, Eds., *More Letters of Charles Darwin* (reprint of 1903 ed., Johnson Reprints, New York, 1971), vol. 1, p. 114.
36. H. J. Muller, "One hundred years without Darwinism are enough," *School Sci. Math.* **1959**, 304 (1959).
37. It remains to be determined to what extent a similar claim can also be made for some of the physical sciences, for instance, the Copernican revolution.
38. In all recent discussions of natural selection, the assumption is made that the concept traces back to the tradition of Adam Smith, Malthus, and Ricardo, with the emphasis on competition and progress. This interpretation overlooks the point that the elimination of "degradations of the type" as the essentialists would call it, does not lead to progress. For the typologist, natural selection is merely the elimination of inferior types, an interpretation again revived by the mutationists (after 1900). Darwin was the first to see clearly that a second factor was necessary, the production of new variation. (This leads to population thinking.) Selection can be creative only when such new individual variation is abundantly available.
39. I greatly benefited from stimulating discussions with S. J. Gould and F. Sulloway, who read a draft of this essay, and from a series of most valuable critical comments, received from Prof. L. G. Wilson, which helped me to correct several errors. My own interpretation, however, still differs in some crucial points from that of Prof. Wilson. Some of the analysis was prepared while I served as Visiting Fellow at the Institute for Advanced Study, Princeton, N.J., in 1970.