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YOUTH AND SCIENTIFIC INNOVATION: THE ROLE OF YOUNG SCIENTISTS IN THE DEVELOPMENT OF A NEW FIELD

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Youth and Scientific Innovation: The Role of Young Scientists in the Development of a New Field

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When the octogenarian Johnny Kelley running in his sixty-first Boston Marathon crossed the finish line, those who witnessed the feat looked on with a mixture of astonishment and admiration. There is a general belief that, within the population as a whole, athletic ability deteriorates with age. Few would consider Kelley—not to mention the other contestants in the masters' division—as evidence to the contrary, even though most people less than half his age could not run even the first leg of the twenty-six mile race. The remarkable Kelley notwithstanding, that athletic contests favour youth is a widely held assumption that is hardly, if ever, seriously questioned.

A far more disputable matter is the relationship between age and ability in science. Physical and mental ability are normally viewed as two very different human attributes, and the connection of the latter with age is not as readily apparent from everyday experience. Yet there is a commonly held belief that as we get older, we may become more set in our way of thinking and less receptive to new ideas. Auguste Comte observed there is a "...perpetual conflict which goes on between the conservative instinct that belongs to age and the innovating instinct which distinguishes youth...."[1] Apparently, the scientific mind is not immune to the effect of aging. "Almost always," Thomas Kuhn claims, "the men who achieve [the] fundamental inventions of a new paradigm have been either very young or very new to the field whose paradigm they changed." So much so, he goes on to say, "this generalization about the role of youth in fundamental scientific research is so common as to be a cliché."[2]

Indeed, it has become a cliché. "The old commonly resist the young, and it is no different in science," is a familiar statement that implies scientists would be arrogant to think otherwise.[3] For some persons, the assertion that age itself has a bearing on scientific work is amazingly naïve.[4] If any-

[1] Comte, Auguste, *The Positive Philosophy*, translated and condensed by Harriet Martineau. Reprint of the 1855 translation of *Cours de Philosophie Positive* published by C. Blanchard, New York, with a new introduction by Abraham S. Blumberg (New York: AMS Press, 1974), p. 518.

[2] Kuhn, Thomas S., *The Structure of Scientific Revolutions*, (Chicago: University of Chicago Press, 1970), p. 90.

[3] Broad, William and Wade, Nicholas, *Betrayers of the Truth: Fraud and Deceit in Science* (Oxford: Oxford University Press, 1982), p. 135.

[4] See Hull, David L., *Science as a Process: An Evolutionary Account of the Social and Conceptual Development of Science* (Chicago: Chicago University Press, 1988), pp. 379-383;

thing, it is not a scientist's age that is relevant, but a number of factors that are correlated with age, such as substantive and methodological preconceptions, professional standing, specialised interests, and affiliation with certain schools of thought.[5] In his account of revolutions in science, Professor I. B. Cohen states "the desire to be an active part of a revolutionary movement is often in conflict with the natural reluctance of any scientist to jettison the set of accepted ideas on which he has made his way in the profession. New and revolutionary systems of science tend to be resisted rather than welcomed with open arms, because every successful scientist has a vested intellectual, social, and even financial interest in maintaining the status quo...."[6]

Nonetheless, there may also be a cognitive aspect to the difficulty aging scientist's have in accepting new ideas. In *The Origins of Modern Science*, Professor Herbert Butterfield argued "...the most difficult mental act of all is to rearrange a familiar bundle of data, to look at it differently and escape from prevailing doctrine."[7] Throughout the course of their careers, scientists develop experimental skills, accumulate data and formulate theories that enable them to perform their work, but paradoxically, may constrain their ability to innovate. According to Professor Kuhn, there is nothing whatsoever unusual about the inability of scientists to reorient themselves to an emerging paradigm. "Lifelong resistance," Kuhn states, "particularly from those whose productive careers have committed them to an older tradition of normal science, is not a violation of scientific standards but an index to the nature of scientific research itself."[8]

The importance of understanding the relationship between age and scientific innovation can be seen in the recent work of Drs. Paula Stephan and Sharon Levin, who explore the implications of demographic changes for the scientific community. If science does indeed favour youth, then they posit that a "graying" scientific community can dampen the rate of scientific discovery.[9] Be that as it may, it is the continuous struggle between emerging theories and established scientific views that permits science to make progress. Whether or not this struggle has a generational dimension to it is an enduring question pondered by scientists and those who study science, alike. It is an admittedly disquieting question that, in the absence of reliable

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Zuckerman, Harriet, *Scientific Elite: Nobel Laureates in the United States* (New York: Free Press, 1977), pp. 164-169.

[5]See Barber, Bernard, "Resistance by scientists to scientific discovery", *Science*, CXXXIV (1961), pp. 596-602.

[6]Cohen, I. Bernard, *Revolution in Science* (Cambridge, Mass.: Harvard University Press, 1985), p. 35.

[7]Quoted in Beveridge, W.I.B., *The Art of Scientific Investigation*, (New York: W.W. Norton, 1957), p. 106. Professor Butterfield has said "of all forms of mental activity, the most difficult to induce even in the minds of the young, who may be presumed not to have lost their flexibility, is the art of handling the same bundle of data as before, but placing them in a system of relations with one another by giving them a different framework...." See Butterfield, Herbert, *The Origins of Modern Science*, Revised Edition (New York: Free Press, 1957), p. 13.

[8]Kuhn, Thomas S., *The Structure of Scientific Revolutions, op. cit.*, p. 151.

[9]Stephan, Paula and Levin, Sharon, *Striking the Mother Lode in Science: The Importance of Age, Place, and Time* (New York: Oxford University Press, 1992), pp. 75-89.

evidence to the contrary, we might be apt to reject out-of-hand were it not for the candid testimonials given by three of the most illustrious scientists of the last three centuries.

Lavoisier, Darwin and Planck

What is perhaps the earliest recorded opinion that innovation in science is more likely to be done by young scientists, is attributed to Antoine-Laurent Lavoisier.[10] In an essay entitled "Réflexions sur le Phlogistique," Lavoisier describes how the prevailing phlogiston theory would eventually give way to his new chemical doctrine based on the role of oxygen:

> I do not expect my ideas to be adopted all at once. The human mind gets creased into a way of seeing things. Those who have envisaged nature according to a certain point of view during much of their career, rise only with difficulty to new ideas. It is the passage of time, therefore, which must confirm or destroy the opinions I have presented. Meanwhile, I observe with great satisfaction that the young people who are beginning to study the science without prejudice, and also the mathematicians and physicists, who come to chemical truths with a fresh mind—all these no longer believe in phlogiston in Stahl's sense.[11]

The new theory which Lavoisier proposed not only fundamentally transformed the field of chemistry, it fixed in the minds of scientists the very meaning of "revolutionary" change in science. Lavoisier's proclamation suggests he understood very well the novelty of his views and thus anticipated the opposition of scientists wedded to established theories.

Lavoisier's ideas on the nature of scientific progress found expression again in Victorian England in the course of another, equally profound revolution in scientific thought.[12] In *On the Origin of Species*, Charles Darwin, like Lavoisier nearly a century before him, appears to anticipate his critics, when he declared: "Although I am fully convinced of the truth of the views given in this volume..., I by no means expect to convince experienced naturalists whose minds are stocked with a multitude of facts all viewed, during a

[10]A century earlier, in his treatise *Of Youth and Age*, Francis Bacon foreshadows Lavoisier when he said: "Young men are fitter to invent than to judge, fitter to execution than for counsel, and fitter to new projects than for settled business."

[11]Lavoisier, Antoine, "Réflexions sur le phlogistique, pour servir de suite à la théorie de la combustion et de la calcination, publiée en 1777." Originally published in *Mémoires de l'Academie des Sciences, année 1783*. Reprinted in *Œuvres de Lavoisier, Tome II, Mémoires de Chimie et de Physique*, (Paris: Imprimerie Impériale, 1862) p. 655. Quoting Lavoisier: "Je ne m'attends pas que mes idées soient adoptées tout d'un coup; l'espirit humain se plie à une manière de voir, et ceux qui ont envisagé la nature sous un certain point de vue, pendant une partie de leur carrière, ne reviennent qu'avec peine à des idées nouvelles; c'est donc au temps de confirmer ou de détruire les opinions que j'ai présentées. En attendant, je vois avec une grande satisfaction que les jeunes gens qui commencement à étudier la science sans préjugé, que les géomètres et les physiciens qui ont la tête neuve sur les vérités chimiques, ne croient plus au phlogistique dans le sens que Stahl l'a présenté, et regardent toute cette doctrine comme un échafaudage plus embarrassant qu'utile pour continuer l'édifice de la science chimique." Translation provided in Gillispie, Charles C., *The Edge of Objectivity: An Essay in the History of Scientific Ideas* (Princeton: Princeton University Press, 1960), p. 232.

[12]See Cohen, I. Bernard, *Revolution in Science op. cit.*, pp. 283-300.

long course of years, from a point of view directly opposite mine." Darwin continued: "a few naturalists, endowed with much flexibility of mind, and who have already begun to doubt the immutability of species, may be influenced by this volume; but I look with confidence to the future,—to young and rising naturalists, who will be able to view both sides of the question with impartiality."[13]

By the mid-nineteenth century, the opinion that older scientists tend to be resistant to new theories had become practically a truism. Indeed, among Darwin's circle of scientific friends, it was something of a lifelong jest that a scientist should not live past sixty "as afterwards he would surely be opposed to all new doctrines."[14] In his autobiography, Darwin recollects how, when Sir Charles Lyell passed his sixtieth year, he reminded Darwin of their youthful oath concerning aging scientists and hoped "that now he might be allowed to live."[15]

Darwin's friend and staunch supporter, T. H. Huxley, is a bit more macabre in his sarcastic humor. In Huxley's biography, his son Leonard recalled his father's fondness for declaring that "...men of science ought to be strangled [at age sixty], lest age should harden them against the reception of new truths, and make them into clogs upon progress, the worse in proportion to the influence they deservedly won."[16] It is the sort of astringent claim that one could easily imagine enlivened the after-dinner conversation at gatherings of Huxley's *x* Club.[17] Perhaps keeping to his word, although ill at the time, upon his sixtieth birthday Huxley duly submitted his resignation as president of the Royal Society. "So the 'day of strangulation' has arrived as last," Sir Michael Foster twitted Huxley, "and with it the humble petition of your friends that you may be induced to defer the 'happy dispatch' for, say at least ten years, when the subject comes up again for consideration."[18]

Following in the tradition of Lavoisier and Darwin was Max Planck. Right from the start of his scientific career at Munich, Planck formed a habit of not shying away from his ideas in deference to scientific authority. In what his supervisors must have considered a terribly impertinent act for a

[13]Darwin, Charles, "On the Origin of Species", reprinted excepts from the sixth (1872) edition in Appleman, Philip, (ed.), *Darwin. A Norton Critical Edition*, (New York: W.W. Norton, 1979), p. 125.

[14]Darwin, Francis, (ed.), *The Autobiography of Charles Darwin and Selected Letters*, first published in 1892 (New York: Dover, 1958), p. 35.

[15]Years earlier, when Lyell was criticized for proposing his own revolutionary ideas in geology, Darwin consoled him with his claim about elderly scientists, See Darwin, Francis, (ed.), *The Autobiography of Charles Darwin and Selected Letters, op. cit.*, p. 35.

[16]Huxley, Leonard, *Life and Letters of Thomas Henry Huxley, Vol. II* (New York: Appleton, 1900), p. 117.

[17]The *x* Club was a small group formed in 1864 by Huxley, J.D. Hooker and a half-dozen other colleagues "...to afford a certain meeting-ground for a few friends who were bound together by personal regard and community of scientific interests..." and entertained the company of such well-known scientists of the era as Darwin, Galton, Agassiz and Helmholtz. See Huxley, Leonard, *Life and Letters of Thomas Henry Huxley, Vol. I op. cit.*, pp. 276-280.

[18]Huxley, Leonard, *Life and Letters of Thomas Henry Huxley, Vol. II op. cit.*, pp. 117-118.

student, Planck's doctoral thesis on the second law of thermodynamics contained a criticism of the concept of irreversibility enunciated by Rudolf Clausius.[19] In contradiction to prevailing views, Planck proposed a sharp distinction between heat conduction and mechanical processes. Planck bluntly stated, "the effect of my dissertation on the physicists of those days was nil. I found no interest, let alone approval, even among the physicists who were closely concerned with the topic. Helmholtz probably did not even read my paper at all. Kirchhoff expressly disapproved of its contents...."[20] As for Clausius, he would not even talk to Planck. When his letters to Clausius went unanswered, Planck travelled to Clausius' home in Bonn in hopes of speaking with him directly, but it was to no avail.

The bitter consequences of postulating a theory that challenged one of the nineteenth-century's most prominent theoretical physicists were so severe, Planck later called it "one of the most painful experiences of my entire life."[21] Though years later, Planck would eventually be proven correct, albeit indirectly, by the work of Ludwig Boltzmann, Planck did not have the satisfaction of being recognised for his contribution. Describing this episode in his life, Planck stated it "may well serve to exemplify a fact which at first sight might appear somewhat strange. An important scientific innovation rarely makes its way by gradually winning over and converting its opponents: it rarely happens that Saul becomes Paul. What does happen is that its opponents die out and that a growing generation is familiarized with the idea from the beginning: another instance of the fact that the future lies with the young."[22] Similarly, in his autobiography Planck said: "This experience gave me...an opportunity to learn a fact—a remarkable one, in my opinion: A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up familiar with it."[23]

Scientific Controversy

Beyond the "creased" or "inflexible" minds of aging scientists, it may very well be the nature of scientific ideas that gives change in science a generational quality. Fundamentally new ideas in science are a magnet for controversy because they are so easily misunderstood or misconstrued. "One of the most frustrating aspects of science," Professor David Hull has said, "is the alacrity with which scientists seem to be able to misunderstand ideas that seem patent to their authors."[24] The confusion may be due in part to the formative state of such ideas when they first appear. As Planck stated,

[19]See Planck, Max, *Scientific Autobiography and Other Papers* (New York: Philosophical Library, 1949); Williams, Trevor I., (ed.), *A Biographical Dictionary of Scientists*, 2nd Edition, (New York: John Wiley & Sons, 1974).

[20]Planck, Max, *Scientific Autobiography and Other Papers, op. cit.*, p. 18-19.

[21]*Ibid.*, p. 30.

[22]Planck, Max, *Philosophy of Physics* (New York: W.W. Norton & Company, 1936), p. 97.

[23]Planck, Max, *Scientific Autobiography and Other Papers, op. cit.*, pp. 29-34.

[24]See Hull, David L., *Science as a Process, op. cit.*, p. 288.

"science does not find ready-made the concepts with which it operates: it has to form them artificially and their perfecting is a gradual process."[25] Perhaps for this reason, as Professor Gerald Holton observed, "all truly great ideas seemed somewhat absurd when first proposed. Indeed, they may be called great ideas precisely because it took the unusual mind to break through the pattern of contemporary thought, to discern the truth behind the mask of a grotesque or trite disguise, to dare to propose the unbelievable or question the obvious. Almost every great innovator, from Copernicus to Niels Bohr, has had to meet initially the skepticism or active opposition of his colleagues."[26]

Misunderstandings may also arise over confusion in terminology. As in the case of Lavoisier, a new theory may come with its own vocabulary, thereby adding greatly to the initial difficulty older scientists may have in comprehending its relevance. Since apart from this, new theories are not readily digested: they require scientists to invest time and effort in understanding their meaning. Unfortunately, "receptiveness" is a misleading term in that it implies a kind of passivity on the part of scientists. More often than not, embracing a new idea requires substantial effort in deciphering its meaning. Scientists may be slow to react to a new theory, if only because of the effort it requires and the many demands already on their time. Kuhn has remarked on the significance of vocabularies when he stated: "If the new viewpoint endures for a time and continues to be fruitful, the research results verbalizable in this way are likely to grow in number. For some men such results alone will be decisive. They can say: I don't know how the proponents of the new view succeed, but I must learn; whatever they are doing, it is clearly right. That reaction comes particularly easily to men just entering the profession, for they have not yet acquired the special vocabularies and commitments of either group."[27] Under these circumstances, it is reasonable that scientists may wait to see the evidence supporting a theory accumulate before committing themselves.

Even more troublesome may be the blunt reality that to persuade someone is "to convince him that one's own view is superior and ought therefore to supplant his own."[28] Planck was deeply affected by his early experience with Clausius. He saw at first hand the conflict that can arise among scientists in their search for truth and the seeming futility of trying to persuade others—particularly if they are in a position of authority. "All my sound arguments fell on deaf ears" Planck complains, "it was simply impossible to be heard against the authority of men like Ostwald, Helm and Mach."[29] But not only did Planck fail to convince them, he did not even have the satisfaction of being vindicated when others did see the truth.

In order to succeed in making a major contribution, scientists must develop a passionate commitment to their research. As Planck's contempo-

[25]Planck, Max, *Philosophy of Physics*, *op. cit.*, p. 115.

[26]Holton, Gerald, *Thematic Origins of Scientific Thought: Kepler to Einstein*, (Cambridge, Mass.: Harvard University Press, 1988), p. 411.

[27]Kuhn, Thomas S., *The Structure of Scientific Revolutions*, *op. cit.*, p. 203.

[28]*Ibid.*, p. 203.

[29]Planck, Max, *Scientific Autobiography and Other Papers*, *op. cit.*, p. 30.

rary, Ivan Pavlov warned scientists, to "remember that science demands from a man all his life. If you had two lives that would not be enough for you."[30] Thus, if truth will eventually win the day, why should a scientist expend not only the effort but risk controversy by engaging in debate with others who are not inclined to share his views? Scientific controversies tend to be prolonged affairs that can become emotionally and physically exhausting to the protagonists. Planck learned quickly that his time was better spent avoiding controversies with the scientific elite. He had too much to contribute to science to become derailed by controversies, which he observed "held comparatively little interest for me, as they could not be expected to produce anything new."[31]

Darwin came to a similar conclusion. "I rejoice that I have avoided controversies," he claims, "and this I owe to Lyell, who many years ago, in reference to my geological works, strongly advised me never to get entangled in a controversy, as it rarely did any good and caused a miserable loss of time and temper."[32] Indeed, a controversy on the scale of that over the "mutability of species" was bound to be long and burdensome. The debate over the ideas in *Origin of Species* is one that would have sweeping implications for modern thought.[33] As Dr. Philip Appleman has remarked, "to the conservative-minded, the terrifying thing about the implications of Darwinism was that nothing was sacrosanct: evolution became not only the science of sciences—worse still, it became the philosophy of philosophies. For those least prepared for change, the impact of all this was shattering."[34]

Because it is frequently a public affair, once one is engaged in a scientific controversy the difficult task of defending one's ideas and position can seldom be avoided.[35] Darwin, who shunned public controversy, was fortunate to have an ally such as Huxley. Huxley was not one to shy away from a scientific debate. Immediately upon reading *Origin of Species*, Huxley wrote to Darwin: "Depend upon it, you have earned the lasting gratitude of all thoughtful men. And as to curs which will bark and yelp, you must recollect that some of your friends, at any rate, are endowed with an amount of combativeness which (though you have often justly rebuked it) may stand in your good stead." Anticipating the outcry over *Origin of Species*, Huxley reassured Darwin "I am sharpening my claws and beak in readiness."[36] Professor Walter Bradford Cannon made the point that "men differ greatly

[30]Pavlov, Ivan P., "Bequest to academic youth" *Science*, LXXXIII (1936), p. 369. Quoted in Beveridge, W. I. B., *The Art of Scientific Investigation*, *op. cit.*, p. 155.

[31]Planck, Max, *Scientific Autobiography and Other Papers*, *op. cit.*, p. 34.

[32]Darwin, Francis, (ed.), *The Autobiography of Charles Darwin and Selected Letters*, *op. cit.*, p. 46.

[33]See Mayr, Ernst, *One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought*, (Cambridge, Mass.: Harvard University Press, 1991).

[34]Appleman, Philip, "Darwin: On changing the mind", in Appleman, Philip (ed.), *Darwin. A Norton Critical Edition*, *op. cit.*, p. 535.

[35]In his examination of controversies among geologists, Hallam notes 'one is struck again and again by the stubbornness or refusal to recant publicly of leading controversialists, in the face of overwhelming evidence.' See Hallam, A., *Great Geological Controversies* (Oxford: Oxford University Press, 1983) p. 157.

[36]Huxley, Leonard, *Life and Letters of Thomas Henry Huxley*, *Vol. I*, *op. cit.*, p. 189.

in their manner of meeting criticism and reacting to it. Huxley found controversy the spice of life. He once testified that a polemic was as little abhorrent to him 'as gin to a reclaimed drunkard.' And a published reply from an opponent evoked the testimony that it 'caused such a flow of bile that I have been better for it since.' All men do not enjoy, however, what Huxley called a 'public war dance.' Some are sensitive and shy; they prefer to live and work in retirement."[37]

Albeit unsettling to the scientists involved in a controversy, there are those who believe that "conflict is a fundamental necessity to the evolution of ideas."[38] Indeed, far from being insidious, Professor Cohen claims that "resistance to change is a source of strength and stability. If every revolutionary idea were welcomed with open arms, utter chaos would be the result."[39] Debates are an essential part of the process by which new scientific ideas become accepted. Scientists, though perhaps not all, can be persuaded by the evidence and do change their minds when confronted by a new scientific idea. "In order to change the direction of development in a field of learning," Professor Holton says, "people's minds must be changed. Even in science this is a slow process, sometimes an impossible one."[40] Professor Cohen calls this process "the winning over of working scientists," which he sees as evidence of the movement from a "revolution on paper" to a "revolution in science."[41] Professor Kuhn also believes that scientists can be persuaded to change their minds. "Though some scientists, particularly the older and experienced ones, may resist indefinitely," he states "most of them can be reached in one way or another."[42]

Nevertheless, the passion of scientists who work to advance the frontier of knowledge can give controversies an intensity that is hard to control. A debate can degenerate from the scientific to the personal, such that it is not only the idea but also the scientist who is under attack. The acrimony that follows can have a lingering effect long after any resolution that might be achieved. Professor Cannon said that "...doubt about the reliability of evidence may persist for a long period after the debated question has been definitively been settled. With persistence of partisan feelings, facts may have their values misinterpreted or the interpretations may be so influenced by prejudice that the facts are really misconstrued."[43]

Scientific debates are essential to the progress of science and controversies are bound to occur. However, the burden of a controversy can weigh heavily on the protagonists, making it difficult to conduct their research.

[37]Cannon, Walter Bradford, *The Way of an Investigator: A Scientist's Experiences in Medical Research* (New York: W.W. Norton & Company, 1945), p. 99.

[38]Holton, Gerald, *Thematic Origins of Scientific Thought, op. cit.*, p. 411.

[39]Cohen, I. Bernard, *Revolution in Science, op. cit.*, p. 35; This sentiment is echoed by Knight, who believes that the "cautious judgment" of older scientists is essential to progress in science. See Knight, David, *The Nature of Science: The History of Science in Western Culture since 1600* (London: André Deutsch, 1976).

[40]Holton, Gerald, *Thematic Origins of Scientific Thought, op. cit.*, p. 412.

[41]Cohen, I. Bernard, *Revolution in Science, op. cit.*, pp. 468-469.

[42]Kuhn, Thomas S., *The Structure of Scientific Revolutions, op. cit.*, p. 152.

[43]Cannon, Walter Bradford, *The Way of an Investigator, op. cit.*, p. 99.

Scientists such as Lavoisier, Darwin and Planck were secure in the belief that science is a search for truth. Rather than debate with the scientists of the day who might take issue with their ideas, they took solace in the belief that young scientists would no doubt see the truth and embrace it. Perhaps Darwin's contemporary, Michael Faraday, offered the best advice when he said, "the real truth never fails ultimately to appear: and opposing parties, if wrong, are sooner convinced when replied to forebearingly than when overwhelmed."[44]

Empirical Evidence on Youth and Scientific Innovation

Were it not for the testimony of great scientists like Lavoisier, Darwin and Planck, perhaps the question of youth and scientific innovation could be dismissed without a second thought. Their authority gives weight to the notion that scientific prowess affords an opportunity to younger scientists. The empirical study of the matter is, however, a difficult task.[45]

Perhaps more than any other scholar, Professor Hull has sought to establish an empirical basis for coming to a conclusion about whether a significant correlation exists between scientists' age and the readiness with which they adopt ideas.[46] Hull and his colleagues have investigated the reception of Darwin's work by British scientists during the decade following publication of *Origin of Species*.[47] His study dealt with 68 scientists who were at least twenty years old in 1859 and still alive in 1869. For each scientist, he determined whether or not he declared in print or correspondence acceptance of the notion of evolution of species. This data is coupled with the age of each scientist in 1859. The data show a significant difference in age between the fifty-two scientists who accepted some form of evolutionary theory and the sixteen who still rejected it: the average age of those who accepted the theory was 40, while those who rejected it was 48.

[44]Quoted in Beveridge, W. I. B., *The Art of Scientific Investigation*, *op. cit.*, p. 112.

[45]The question of the role of young scientists in scientific innovation as it has developed from Lavoisier, Darwin and Planck is quite separate from the question of age and scientific productivity, which has been extensively discussed in the literature. For example, see: Allison, Paul D. and Stewart, John A., "Productivity differences among scientists: evidence for cumulative advantage", *American Sociological Review*, XXXIX (1974), pp. 596-606; Cole, Stephen, "Age and scientific performance", *American Journal of Sociology*, LXXXIV (1979), pp. 958-977; Fox, Mary Frank, "Publication productivity among scientists: A critical review", *Social Studies of Science*, XIII (1983), pp. 285-305; and the classic, Lehman, Harvey C., *Age and Achievement* (Princeton: Princeton University Press, 1953). This question is also different from the issue of age and major scientific discoveries. For example see Zuckerman, Harriet, *Scientific Elite*, *op. cit.*

[46]Hull provides an exhaustive survey of the literature as it pertains to the issue, particularly with regard to Planck. See Hull, David L., *Science as a Process*, *op. cit.*, p 379. Although Hull is comfortable lining up authors pro and con, what is most evident from his effort is the degree to which Planck's statements are much quoted but seldom investigated. In instances where data are available, studies may be ambiguous because they are directed at other questions. For example, see McCann, H. Gilman, *Chemistry Transformed: The Paradigm Shift from Phlogiston to Oxygen* (Norwood, NJ: Ablex Publishing, 1978).

[47]The original study is reported in Hull, David L., Tessner, Peter D. and Diamond, Arthur M., "Planck's principle", *Science*, CCII (1978), pp. 717-723; the results are further discussed in Hull, David L., *Science as a Process*, *op. cit.*, pp. 379-384.

Professor Hull is, however, more than a little suspicious of this simple result. Although the scientists who continued to believe in the immutability of species after 1869 were on average older than those who changed their minds, Hull shows that age alone explains less than ten percent of the variation in this latter group.[48] Hull also examines the lapse of time among those who eventually accepted Darwin, and he found no difference in age. As he put it "older scientists were just as quick to change their minds as younger scientists."[49] Furthermore, when the data were analyzed by age cohorts, the proportion of those who refused to accept the theory in each cohort is greatest for scientists fifty or older, followed by the youngest cohort. The middle cohorts, between ages thirty and fifty, are least likely to have rejected it.[50]

In the absence of strong empirical evidence, Professor Hull is highly skeptical of what he calls Planck's principle. "The conceptual rigidity of aging scientists is often held to be as psychologically inevitable as the stiffening of their joints.... Such prejudice against the aged is all the more amazing because it is based on only the most casual observations."[51] Thus, he considers the idea that young scientists are more positive in their response to new ideas as no more than the result of a "selective blindness" based on anecdotal evidence.

Nonetheless, the persuasiveness of Hull's empirical evidence is qualified by the relatively small sample, as well as other factors that severely limit analytical refinement. For example, it is extremely difficult to rule out the potential for significant heterogeneity within the sample that may influence the results. This is particularly relevant considering what is meant by "Darwinism." Defining Darwinism is difficult, and whether someone can be said to have accepted it, is not as straightforward as it might seem. Professor Ernst Mayr, for example, says that Darwinism can be viewed as five distinct concepts: evolution, common descent, gradualism, multiplication of species, and natural selection.[52] Most evolutionists of the period other than Darwin did not accept all five. This is true even in the case of Huxley. Though he agreed with the idea of common descent, Mayr argues he did not accept gradualism or the multiplication of species, and was either ambivalent or contradictory about natural selection. Scientists in the sample varied in their

[48]Hull, David L., *Science as a Process, op. cit.*, pp. 380. The same result is found by one of Hull's colleagues in a study of cliometrics and is seen as support for human capital theory in economics. See: Diamond, Arthur M., "Age and the Acceptance of Cliometrics", *Journal of Economic History*, XL (1980), pp. 838-841.

[49]Hull, David L., Tessner, Peter D. and Diamond, Arthur M., "Planck's Principle", *op. cit.*, p. 722.

[50]Although Hull considers this evidence to refute the basic hypothesis, it should be noted that scientists in the oldest cohort are twice as likely to reject than those in the youngest cohort. In comparison, Allen's study of thirty-five prominent biologists active at the turn of the century finds a generational difference between evolutionists and hereditary theorists. See Allen, Garland E., "Naturalists and experimentalists: The genotype and the phenotype", *Studies in the History of Biology*, III (1979), pp. 179-209.

[51]Hull, David L., *Science as a Process, op. cit.*, p 379.

[52]Mayr, Ernst, *One Long Argument, op. cit.*, pp. 35-38.

attitude toward different aspects of Darwinism, and some were already in agreement with certain elements of evolutionary thought before 1859.[53]

The case of Lyell is especially indecisive in this regard. According to Hull, Lyell's age at the earliest indication of acceptance was 70, thus implying Lyell's acceptance of Darwinism was eight years after the publication of *Origin* in 1867. Writing to Darwin on October 3, 1859, just days after receiving proofs of *Origin*, Lyell congratulated Darwin on his "grand work," calling it "a splendid case of close reasoning," and saying "right glad I am that I did my best with Hooker to persuade you to publish it...." Lyell also made a point of correcting a statement Darwin had made in *Origin*: "surely it cannot be said that the most eminent naturalists have rejected the view of the immutability of species?" The following month Hooker wrote to Darwin regarding Lyell's reaction to *Origin*. Hooker, with whom Lyell was staying, related that Lyell "is perfectly enchanted, and is absolutely gloating over it." Lyell's exact position on the mutability of species would become less certain over the next few years when Lyell would not fully back the thesis publicly—an action which clearly confused his friend Darwin. Writing to Lyell in March 1863, Darwin stated: "As you say that you have gone as far as you believe on the species question, I have not a word to say; but I must feel convinced that at times, judging from conversation, expression, letters, &c., you have as completely given up belief in immutability of specific forms as I have done."[54]

The findings in Hull's study are also difficult to interpret in light of the possibility of bias in the data. By setting a limitation on the minimum age of a scientist in 1859 (i.e., twenty years old), the sample is truncated in order to omit "those scientists who were raised as Darwinists."[55] But eliminating these young scientists from the sample seems to contradict precisely what Planck meant when he said "a new generation grows up that is familiar with" the new doctrine. Furthermore, by focusing on scientists who left a public record of their position, the sample may be biased toward those who were the most prominent scientists of the decade. Hull believes this is less of a problem, since it would over represent "young Darwinists," who left more of a public record given the success of Darwin, and underrepresent young scientists opposed to the evolution of species.

Professor Hull's investigation of the relationship between youth and scientific innovation shows how difficult even simple hypotheses about this relationship are to study. Dr. Peter Messeri has examined the rate of acceptance of a sample of 96 North American scientists actively engaged in geophysical research during the 1960s and early 1970s.[56] The dependent

[53]According to Hull's data, four of the fifty-two scientists who accepted evolution of species did so before 1859. See Appendix H in Hull, David L., *Science as a Process, op. cit.*, pp. 533-534.

[54]Lyell, Charles, *Life, Letters and Journals, Vol. II*, (London: J. Murray, 1881) p. 325; Darwin, Francis, (ed.), *The Autobiography of Charles Darwin and Selected Letters, op. cit.*, pp. 218, 223, 271.

[55]Hull, David L., Tessner, Peter D. and Diamond, Arthur M., "Planck's principle", *op. cit.*, p. 719.

[56]Messeri, Peter, "Age differences in the reception of new scientific theories: The case of plate tectonics", *Social Studies of Science*, XVIII (1988). Using annual editions of the *Science*

variable in the analysis is the date of adoption of plate tectonics, *i.e.*, the "mobilist programme" as ascertained from the scientist's published articles. The independent variable is the scientist's "age," which is defined as the length of his professional tenure (*i.e.*, the number of years since the receipt of his highest degree), when he adopted the mobilist theory.[57] The sample is divided in younger and older cohorts based upon whether the scientist's doctorate was granted before or after 1955.

Using a non-parametric hazard rate technique based on the life table method, Messeri's data indicate that in the earlier years the older cohort is more likely than the younger cohort to have adopted the mobilist research programme. It was not until later, after the mobilist programme had become generally accepted, that the younger cohort was more likely to have adopted it. Messeri also shows that in the early years of the period covered by the sample, those who accepted the mobilist theory were about twenty years "older" (i.e., in terms of professional experience) than those who refused it. In the later years, the situation is reversed so that those who accepted it are about five years younger than those who did not do so.[58]

Dr. Messeri's conclusion is that contrary to the view that young scientists accept new theory more readily than older ones, younger scientists were not among the first to accept plate tectonic theory. He believes that it is because of their reluctance to become involved in a controversy. He argues that "most of those engaged in the debate were middle-aged and older scientists, while younger scientists prudently refrained from making rash public announcements." The "high risk context" of the early stages of the emergence of a new theory "exacts some perceived or actual professional costs" and this is conducive to the readiness of senior scientists who are secure in their standing and most able to defend their views. Nonetheless, Dr. Messeri admits the sample is "not statistically representative of a well-defined population."[59] The sampling procedure is biased toward scientists who eventually adopted the "mobilist programme" and is not sufficiently representative of those who would not accept it because it does not include geologists who ignored the mobilist doctrine altogether.[60]

Citation Index from 1964 through 1974, Messeri created his sample collecting senior authors of articles that cited one or more of eleven seminal "mobilist" articles published between 1961 and 1968. This process yielded 2200 authors. Messeri than created a sub-sample consisting of authors who published at least one article in 1966 and continued to publish at least one article per year through 1970, which he calls the period of "peak conversion." A random sample of this sub-sample was created and only those authors who were found in recent editions of American Men and Women of Science were selected for analysis. To this group were added nine member of the National Academy of Sciences, to serve as representatives of the scientific elite.

[57] It is generally agreed that "professional age" or tenure is a more appropriate measure than biological age. Dr. Messeri faces the same difficulty as Dr. Hull in judging what it means to have "adopted" the mobilist programme.

[58] The basic conclusion of the analysis of age and adoption is confirmed by a fully specified hazard rate model with covariates.

[59] Messeri, Peter, "Age differences in the reception of new scientific theories", *op. cit.*, p. 101.

[60] Moreover, by sampling only senior authors, Messeri's data may underrepresent younger scientists.

In contrast to Dr. Messeri, a study by Dr. Matthew Nitecki and his collaborators suggests just the opposite. The earlier the receipt of one's degree, the longer the delay between the encounter with the theory of plate tectonics and its acceptance.[61] His sample consists of 208 geologists randomly selected from the fellows of the Geological Society of America and members of the American Association of Petroleum Geologists. The conclusion may be difficult to defend. The statistical significance of the finding is not established, nor is it clear that it could be, given the design of the survey and the questionnaire.

In another study of geologists, Professor John Stewart has found that the most prominent scientists resisted the theory of continental drift but that age is not a factor in explaining resistance.[62] Professor Stewart examined 77 scientists who published opinions on the theory between 1907 and 1950. The dependent variable is the extent of acceptance of the theory of continental drift by scientists as indicated in their first published views about it. After accounting for "intellectual investments in terms of publications," age is not found to be significant in explaining a scientist's attitude toward the theory.[63] However, the conclusions must be assessed in light of the relatively small sample.

In sum, the empirical results of investigations of the relationship of youth and scientific innovation are mixed.[64] While there is little evidence of a correlation between age and the adoption rate of new theories, most investigators acknowledge the difficulty of dealing with the question con-

[61] Nitecki, Matthew H., Lemke, J. L., Pullman, Howard W. and Johnson, Markes E., "Acceptance of plate tectonic theory by geologists", *Geology*, VI (1978), pp. 661-664.

[62] Stewart, John A., "Drifting continents and colliding paradigms: A quantitative application of the interests perspective", *Social Studies of Science*, XVI (1986), pp. 261-279. Also see Stewart, John A., *Drifting Continents and Colliding Paradigms: Perspectives on the Geoscience Revolution* (Bloomington: Indiana University Press, 1990).

[63] In his memoir, the geologist Dr. H. W. Menard expresses a similar conclusion: "Age did not affect the creativity, imagination, or boldness of the inventors of sea-floor spreading and plate tectonics. The marine exploration and discovery were mainly the work of men in their early thirties, although the early leaders...were in their forties." But Dr. Menard goes on to suggest that "the age relation, however merely reflected the great influx of young men as oceanography began its rapid expansion." See Menard, H. W., *The Ocean of Truth: A Personal History of Global Tectonics* (Princeton: Princeton University Press, 1986), p. 298.

[64] Although the discussion is confined to quantitative studies, qualitative studies touching upon the question also tend to be mixed. For example, on an interview tour of research institutes, Professor John Ziman found little evidence of a view that scientific innovativeness declines with age. "My own feeling is that the evidence presented here is against such a strongly deterministic principle, but all our everyday experience of people suggest there is a good deal of truth in the precepts that people do get less flexible as they grow older...." Ziman quotes one scientist: "I don't believe, on the whole, that people go off with age as much as is said. I think you've got bad scientists who start off not very good, and then when they get to their forties and fifties they pack up altogether—and we all know a few! But I think the good scientists, most of them anyway, keep going very well, and I know many in their sixties who are still pretty smart, and in a way you're sorry to see them pack up.... On the whole, they're the better ones to start with—and I know very few.... I know of very few who were damn good scientists when they were young who haven't stayed damn good scientists." See Ziman, John, *Knowing Everything About Nothing* (Cambridge: Cambridge University Press, 1987) p. 78.

clusively. The obvious technical concerns of sample size and research design aside, the main difficulty lies in comprehension of the dynamics of a process that evolves over a long period of time. As these studies show, it is difficult to know who are the scientists who might have adopted a theory but did not. As Hull states, it may very well be the case that young scientists might commit their careers to the investigation of ideas which leave no mark."[65]

Young Scientists and the Study of Neural Networks

We ourselves have investigated the question of age and scientific innovation in a recent international survey of scientists working on the development of neural networks. Although the study of neural networks has a long history, it was not until the mid-1980s that the field gained widespread recognition as a promising area of research.[66] Indeed, prior to that, the field suffered a low level of legitimacy among scientists for nearly two decades. This was because many scientists thought that research problems were insurmountable given the state of knowledge in the field and, in part, due to the belief among some prominent scientists that alternative areas of research were far more promising avenues to pursue. The controversial nature of neural networks during what one scientist called the "wilderness years," provides an opportunity to examine the role of young scientists in the development of a field.

In our sample of 720 neural network scientists, we found evidence to suggest that young scientists had played a major role in populating the field during its emergence over the past decade.[67] In Table 1 we show the distribution of neural network scientists according to the number of years of professional experience they had (*i.e.*, the number of years which elapsed since graduation). Scientists who had not yet receive their degree are categorized as students. The largest cohort, with more than one-quarter of all neural network scientists, had between zero and four years of professional experience. The two youngest cohorts—students and scientists with less than five years of experience—accounted for over 40 percent of the 720 neural network scientists.

The relative youthfulness of the neural network research community must be gauged relative to the age structure of the scientific community as a whole. For this purpose, we use historical data for doctoral scientists and engineers educated and employed in the United States. The data for the scientific community are adjusted in order to reflect the relative distribution of fields represented in the neural network community. Table 1 provides the distribution of a subsample of 346 neural network scientists—those who were employed and educated in the United States—so that a comparison can be made with the matched sample of the scientific community.

[65]Hull, David L., *Science as a Process, op. cit.*, p. 383.

[66]Appendix A

[67]Appendix B provides a description of the data collection procedures and sample characteristics.

TABLE 1

The Age Structure of the Neural Network Research Community Relative to the Scientific Community as a Whole

	Percentage of Neural Network Scientists		*Percentage of All Scientists*
	Total	*U.S. Educated & Employed*	*U.S. Educated & Employed* [a]
Years since graduation:	(N = 720)	(N = 346)	(N = 39,666)
Students	15.4	17.3	16.8[b]
0 to 4 years	27.4	28.6	13.2
5 to 9 years	18.7	19.1	14.7
10 to 14 years	13.8	13.6	14.8
15 to 19 years	11.4	9.2	14.8
20 or more years	13.3	12.1	25.6

SOURCES: Data for the neural network research community: *M.I.T. Survey of the Neural Network Community, 1990* conducted by the authors. Data for the scientific community: National Research Council and National Science Foundation, *Survey of Doctoral Recipients, 1989* (Washington, D.C., 1992); National Science Foundation, *Selected Data on Science and Engineering Doctorate Awards: 1991*, NSF 92-309 Selected Data Tables (Washington D.C., 1992).

[a] Data for U.S. educated and employed doctorates in 1989. The sample is matched with the neural network community based upon the distribution of fields represented in the survey: electrical engineering (36%), physical science (19%), computer science (18%), life science (7%), mathematics (7%), and psychology and cognitive science (5%).

[b] The percentage of doctoral students in the scientific community is estimated from the number of doctorates granted over a four-year period from 1988 to 1991.

There was a marked difference between the age structure of the neural network scientists and the scientific community as a whole. The data indicate that young scientists were more likely to populate the field of neural networks during its emergence over the past decade. Among the sample of neural network scientists educated and employed in the United States, 46 percent were students or scientists with less than five years of professional experience. In the case of the scientific community as a whole, 30 percent were students or had less than five years of professional experience. Furthermore, at the opposite end of the distribution, 40 percent of the scientific community had fifteen or more years of professional experience, compared to 21 percent for the neural network community.

There were two cohorts in which the difference between neural network scientists and the scientific community was particularly large. Scientists with between zero and four years of professional experience accounted for 29 percent of the neural networks community and for 13 percent of the scientific community. Furthermore, the cohort of scientists with twenty or more years of professional experience accounted for 12 percent of the neural network community and for 26 percent of the scientific community. Looked at in a another way, the neural network community had more than twice as many scientists in the youngest cohort (after students) than it had in the oldest cohort. This is diametrically opposed to the scientific community as a whole, which had only half as many scientists in the youngest cohort (after students) than it had in the oldest cohort. Hence, the distribution of scientists in the field of neural networks cannot be explained simply in terms of the age structure of the scientific community as a whole.

The relative youth of the neural network community may be the result of the rapid increase in the number of young scientists entering the field during the 1980s. To examine this question we divided the sample into two categories according to when a scientist entered into the field of neural networks, as reported by each respondent about his own activities. "Early entrants" are those scientists who entered the field prior to its period of rapid growth which began by 1983, while scientists who entered the field thereafter are classified as "late entrants". We examined the age of scientists when they entered the field of neural networks and found that early entrants were on average six years younger than their colleagues who entered later: 31 years of age for early entrants, compared with 37 years of age for late entrants. While two-thirds of the scientists who entered the field of neural networks did so very early in their professional career—as students or within five years of graduation—in the case of early entrants, it was even more likely that they were younger at the time.

Our survey also inquired about the factors that might have influenced a scientist's decision to initiate research in neural networks. A comparison of early and late entrants indicates that early entrants were more influenced by their intellectual interest in neural networks and less influenced by such factors as the opinions of leading scientists, successes of other scientists, potentiality for gaining recognition from other scientists, availability of financial support, and lack of other topics to pursue.

Educating Young Scientists

According to Professors David Edge and Michael Mulkay, "it is clear from various reports on the emergence of scientific specialties that recruitment of graduates and other researchers is often difficult in the period before major discoveries have been made and before the scientific reputation of the new specialty has been established. During this period young scientists seldom choose to enter the new field unless they are actively encouraged by those already involved."[68] The late Nicholas Mullins described how the recruitment of young scientists helped to sustain the momentum of molecular biology in the early years.[69] Similarly, one member of the first cohort of doctoral students to complete their dissertation in quantum mechanics in America—John Van Vleck—recollects the rapid growth of quantum theory within the American physics community in the 1920s:

[68]See Edge, David O. and Mulkay, Michael J., *Astronomy Transformed: The Emergence of Radio Astronomy in Britain* (New York: John Wiley & Sons, 1976), p. 22. Also see Lemaine, Gerard, MacLeod, Roy, Mulkay, Michael J. and Weingart, Peter, *Perspectives on the Emergence of Scientific Disciplines* (Chicago: Aldine Publishing Company, 1976).

[69]Mullins, Nicholas C., "The Development of a Scientific Specialty: The Phage Group and the origins of molecular biology", *Minerva*, X (1972), pp. 51-82. See also Griffith, Belver C. and Mullins, Nicholas C., "Coherent Social Groups in Scientific Change", *Science*, CLXXVII (1972), pp. 959-964.

"Although we did not start...quantum mechanics, our young theorists joined it promptly." Professor Holton notes the "venturesome spirit" among Van Vleck's young colleagues at Harvard, which countered the "reigning hesitancy about embracing quantum ideas."[70]

Young scientists come to a new field unencumbered by a large accumulation of knowledge. They are more likely to embrace a new field without the hesitancy that comes from being too cognizant of prevailing opinions of what is or is not a legitimate area of research. Such naïveté may work in favour of young scientists, helping to sustain their enthusiasm for grappling with what more experienced scientists might consider to be insurmountable problems. It may very well be that "knowing too much" is detrimental to the development of the potentiality of a young scientist. Perhaps no one knows this better than Professor James Watson, who has said:

> If education is too long it will probably kill you as a scientist. That's why it's nice if in some way we can put people into a position where they can begin to do science not much after twenty. It's a shame to wait any longer; even then, you see, you are groping at first. It probably takes a few years before you know what sorts of questions people are trying to answer, but can't. And, you say you have to know all these facts—well, clearly the facts, some of them, that you learn are wrong, so if you take them too seriously you won't discover the truth. You could say that if you become too imbued in the ideas and talk about them too long, maybe your capacity for ever believing they're false would be burned out. Probably what you should learn if you're a graduate student is, not a large number of facts, especially if they're in books, but what the important problems are, and to sense—which experiments, work that's been done, probably...aren't quite right. And which things you'd like to do yourself if a method came up to do it.[71]

Our own study of the field of neural networks suggests that scientists may develop an inclination for pioneering research very early in their professional career. If, as Horace Freeland Judson asserts, "science is a calling that comes in adolescence,"[72] then it makes good sense to nurture the venturesome spirit of young scientists in the course of their education. The process of choosing a dissertation problem is of critical importance in this respect. Striking a balance between a supervisor's interests and personal autonomy is inevitably difficult, but it is likely that some students are too ready to yield responsibility for problem choice to their supervisors. Professor Ziman recalls: "We often forget that the commonest occasion for asking the question 'What research shall I do now?' is when the graduate student goes to a research supervisor for advice on a topic for his dissertation; *i.e.*, to be given a scientific problem which is both 'do-able' and 'worth doing.'"[73] While there is nothing objectionable in and of itself to seeking such advice, one is left with the impression that students would be better served if they began testing their own scientific judgment by taking greater initiative in identifying and choosing research problems.

[70] Quoted in Holton, Gerald, *Thematic Origins of Scientific Thought*, *op. cit.*, p. 172.

[71] Judson, Horace Freeland, *The Eighth Day of Creation: The Makers of the Revolution in Biology* (New York: Simon & Schuster, 1979), p. 45.

[72] *Ibid.*, p. 47.

[73] Ziman, John, "What are the Options? Social Determinants of Personal Research Plans," *Minerva*, XIX (1981), p. 10.

A molecular biologist who has carefully studied the process of scientific discovery asserts that highly successful scientists usually had an early opportunity to do independent research.[74] Professor Robert Scott Root-Berstein says "by 'independent' I emphatically do not mean the sort of advisor-oriented 'independent' research that doctoral [and post doctoral] students...do these days, in which the problem, the techniques, and the evaluation are the advisor's. I mean that the young researcher identifies the problem, learns or invents the techniques for carrying out the research, and evaluates the results. By 'early,' I mean either by the age of twenty-two (preferably considerably earlier) or, if the researcher entered science late, within a year of beginning doctoral studies."[75]

Young scientists can play a special role in the growth of science in the way they populate new fields of research. As they embark on their careers, they have a unique opportunity to explore the problems of a field of science. This opportunity may be squandered by imposing on young scientists a view of science as a given set of facts and problems to master. Rather what may be needed is to develop a view of science as a process, as knowledge in the making, in which the skills of exploring and judgment in choosing problems are equally as important as mastering that which is known. Insofar as they become passionately committed to their chosen research, young scientists may contribute greatly to the emergence of new fields that otherwise might be ignored by the majority of practicing scientists.

Appendix A: Neural Networks: A Brief of the Field

A neural network is a type of information processing system that is inspired by models of the human brain. A neural network system has certain features that make it unique in form and function from conventional computers. For example, a neural network is not programmed in the usual sense, but rather it is trained with data. This implies that the computational performance of a neural network improves with experience: as it processes more and more information in performing a task, it becomes increasingly more accurate in its response. Another feature is its degree of parallelism in processing a task. Unlike a normal computer with a single or small number of sophisticated central processing units, a neural network has a very large number of simple processing elements that operate simultaneously on a computational problem. These features allow it to perform certain tasks that

[74]Examples of successful scientists include Darwin, Maxwell, Joule, Planck, Einstein, J.J. Thomson, E.O. Lawrence, Dobzhansky, J B.S. Haldane, H.J. Muller, and James Watson. See Root-Bernstein, Robert Scott, *Discovering: Inventing and Solving Problems at the Frontiers of Scientific Knowledge* (Cambridge, Mass.: Harvard University Press, 1989).

[75]Root-Bernstein, Robert Scott, *Discovering Inventing and Solving Problems at the Frontiers of Scientific Knowledge* (Cambridge, Mass.: Harvard University Press, 1989), p. 387. The importance of an early opportunity to do research can also be seen in the data on Nobel laureates. The median age of American educated laureates when they received their degrees is 25 years compared with a median age of 30 years for a matched sample of doctorates in science, in general. Professor Zuckerman attributes this difference in age to "the fact that laureates started their graduate work earlier and also took less time to complete it." See Zuckerman, Harriet, *Scientific Elite, op. cit.*, p. 89.

otherwise might be very difficult using existing computer technology. Neural networks are also referred to as connectionist systems, adaptive systems, or neurocomputers.[76]

Neural networks have a considerable history of development, stretching back to theoretical explanations of the brain and cognitive processes proposed during the 1940s. In the early years, scientists formulated and elaborated basic models of neural computing that they then used to explore phenomena such as adaptive stimulus-response relations in random networks. By the 1960s there were several efforts to implement neural networks, the most notable being the single-layer "perceptron." Among neural network scientists the perceptron was considered a watershed, but at the same time it served as a lightning rod for criticism from scientists more interested in the burgeoning field of artificial intelligence. The idea of neural networks, as exemplified by the perceptron, quickly became seen as almost antithetical to the symbolic reasoning principles of artificial intelligence. Critical analysis of the perceptron led some highly respected scientists in the field of artificial intelligence to proclaim that the concept was fundamentally flawed, and as such, inappropriate for scientists to waste much effort on. By casting doubt as to its legitimacy, antagonists of neural networks may have effectively dissuaded other scientists from entering the field in larger numbers.[77]

The controversy surrounding neural networks notwithstanding, work continued during the early 1970s by perhaps no more than a few hundred scientists worldwide. Undeterred in their belief of the potential of neural networks, their persistence over the next decade eventually bare fruit. By the 1980s, neural networks began to be viewed in a new light by scientists in a variety of disciplines, so that the field soon achieved a position of legitimacy within the scientific community. A professional society for neural network scientists was formed, specialised journals and books were published, and the first in a series of international conferences were held. Interest in the field became widespread, so that the number of scientists working on neural networks expanded rapidly. By the end of the decade the size of the field grew in membership from a few hundred to several thousand scientists worldwide.

Appendix B: The Neural Network Community Survey: Method and Data

Through an analysis of published sources, including books, journal articles, and conference proceedings for the two-year period from 1988 to 1989, we identified more than 3,000 scientists working throughout the world on the subject of neural networks. We were able to determine the exact address for each of 2,037 scientists in thirty-five different countries. A questionnaire was determined to be the most appropriate method of investi-

[76] For further details, see *DARPA Neural Network Study* (Fairfax, Virginia: AFCEA International Press, 1988).

[77] See Papert, Seymour, "One AI or many", *Dædalus*, CXVII (Winter 1988), pp. 1-14; Minsky, Marvin and Papert, Seymour, *Perceptrons: An Introduction to Computational Geometry, Expanded Edition* (Cambridge, Mass.: MIT Press, 1988).

gation. A twelve-page questionnaire in English was sent to scientists inquiring about (a) their activities in the study of neural networks, (b) their decision to begin working on neural networks, (c) factors that might lead them to cease their research in neural networks in favour of another field, (d) their interaction with the rest of the community of scientists in the field of neural networks, and (e) their demographic characteristics. The questionnaire was pretested in the United States. Additional tests were conducted in Europe to reduce potential difficulties which might arise among those respondents for whom English is a second language.

Since there were thirty-seven scientists with more than one address during the time period considered, a total of 2,074 questionnaires were mailed in February 1990. After the third week of data collection, we sent a follow-up letter and posted e-mail messages on computer bulletin boards to alert neural network scientists of the survey. Of the 2,074 questionnaires, 162 were returned as undelivered by the post office. At the completion of the period of data collection approximately ninety days later, 720 of the 1,875 questionnaires presumed to be delivered were completed and returned, yielding a final response rate of 38.4 percent. Some of the factors that may have affected the response rate include: the length of the questionnaire, the global scope of the survey, and the institutional mobility of scientists.

In order to rule out apparent biases attributable to "self-selection," demographic comparisons were made to determine whether the survey population departed significantly from the sample of respondents. In particular, first-order comparisons between the two groups were made with respect to the geographic location of a respondent's institutional affiliation, type of institutional affiliation, and disciplinary background.

First, a geographic comparison was made grouping the respondents in the sample and in the survey population into four regions: the Americas, Europe, the Far East, and the Middle East. Of the 720 respondents, 63 percent reside in the Americas (all but a few percent in the U.S.), 25 percent in Europe, ten percent in the Far East, and about two percent in the Middle East (mainly Israel). These percentages coincide almost perfectly with the survey population (χ^2=5.24, d.f.=3, n.s.). Similar results were achieved when omitting the smallest category (the Middle East) from the test.

A second test compared the respondent sample and survey population with respect to the institutional affiliation. Respondents were classified into three categories: universities, industrial firms, or other types of institutions (mostly government funded laboratories that are not university-based). Among the 720 respondents, 452 (63 percent) are affiliated with academic laboratories, 177 (25 percent) are employed in industrial firms, while 91 (12 percent) are engaged in other types of institutions. A comparison reveals that no statistically significant departure exists between the respondent sample and the survey population (χ^2=5.61, d.f.=2, n.s.).

A final, albeit less precise, test compared the disciplinary background of the sample respondents with those of the survey population. Although respondents indicated their disciplinary backgrounds, for the survey population we were only able to infer scientists' disciplines from their postal address when a departmental affiliation was provided (e.g., scientists belonging to electrical engineering departments were classified as electrical engineers). Upon careful inspection of the survey population, the disciplinary background for about 1,500 scientists was found. Using this data, we found no significant difference when comparing respondents with the survey population. The disciplines most represented among respondents included electrical engineering (36 percent), physical sciences (19 percent), computer science (18 percent), biological sciences and engineering (7 percent), mathematics (7 percent), and psychology and cognitive science (5 percent).

Sample characteristics

The 720 respondents were employed in 220 different academic institutions, 101 industrial firms, and 62 other (mostly governmental) types of organizations. There are 89 respondents who reported more than one employer. The large majority of respondents (82 percent) held a doctorate or were in the process of obtaining one. Only 16 percent reported holding a master's degree as their highest academic degree, and just two percent had only a bachelor's degree. The distribution of academic degrees was further reflected in the respondents' current positions of employment. The majority of them were university teachers—38 percent—or hold a scientific appointment—32 percent—ranging from staff scientist to chief scientist. About 17 percent of the respondents were students, virtually all of whom are in doctoral programmes.

The average respondent is 37 years old (s.d.= 9.2 years). The respondent sample ranges in age from 22 years for the youngest to 69 years for the oldest, with the youngest quartile between ages 22 and 30 and the oldest quartile between ages 43 and 69. The median age is 35 years. For the 702 respondents who specified the year they began working on neural networks, the average length of time in the field is 6.2 years, (s.d.= 6.1 years). The median length of time in the field is four years, with the range between one and 40 years.

The respondents were classified as "early" or "late" entrants based upon when they entered the field. The line separating "early" from "late" was determined through an historical analysis of the field and an examination of the cumulative entry over time of respondents into the field. As a result of these procedures, 25 percent of the respondents were classified as early entrants and the remaining 75 percent were classified late entrants.

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