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High Cognitive Complexity and the Making of Major Scientific Discoveries

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Introduction[1]

This essay is derived from insights developed from a complex research project about major discoveries in the basic biomedical sciences of Britain, France, Germany and the United States during the entire twentieth century. Focusing on 291 major discoveries, that study was designed to understand the organizational and laboratory context in which major discoveries occurred.[2] In the process of conducting the study, I began to observe distinct social psychological characteristics of the scientists involved in making these discoveries. This essay reports some of these findings, with somewhat modest goals. And this essay is a preliminary report on some aspects of the social psychological profiles of many scientists who made major discoveries in basic biomedical science.

Focusing on individual scientists involved in making major discoveries, I do not attempt to develop a theory of discovery or of creativity. Because there is no consensus in the literature on the meaning of creativity, the essay deliberately avoids focusing on creativity. The term creativity has been used to address so many different problem areas that it has lost much of its utility as a research concept. People talk about the creative baker, the creative gardener, the creative taxi driver, the creative coach. One writer has listed over a thousand definitions of creativity. When a term is so overused and frequently misused, it is best to find an alternative concept for analytical purposes. For this reason, this essay employs the concept 'high cognitive complexity' to advance our understanding of the scientists who make major discoveries.

Those with high cognitive complexity have the capacity to understand the world in more complex ways than those with less cognitive complexity. For reasons described below, scientists having high levels of cognitive complexity tend to internalize multiple fields of science and have greater capacity to observe and understand the connectivity among phenomena in multiple fields of science. They tend to bring ideas from one field of knowledge into another field.[3] High cognitive complexity is the capacity to observe and understand in novel ways the relationships among complex phenomena, the capacity to see relationships among disparate fields of knowledge. And it is that capacity which greatly increases the potential for making a major discovery. Every one of the 291 discoveries in our larger research project reflected a great deal of scientific diversity. And in our larger body of work on scientists and major discoveries we argue that a major indicator of high cognitive complexity for scientists is the degree to which they internalize cognitively scientific diversity. Indeed, a necessary condition for making a major discovery was that the scientist had to internalize a high level of cognitive complexity. For this reason, an intriguing and important problem is to understand why scientists vary in having high levels of cognitive complexity. On the other hand, most scientists having high cognitive complexity do not make major discoveries.

This essay develops three separate but complementary agenda. First, it briefly reports on the social contexts of the laboratories in which the 291 major discoveries occurred. The structure of these laboratories enhanced their success in integrating novel perspectives on important problems from diverse fields of science. Second, the essay argues that most of the scientists who made the 291 major discoveries internalized a great deal of scientific diversity. It was that characteristic which facilitated their capacity to work in multiple fields simultaneously, and a major goal of the essay is to address the question of why they had high cognitive complexity. Third, the essay demonstrates the consistency of these findings about the process of discovery and high cognitive complexity with some of the literature which has been emerging for some years in certain areas of neuroscience. For example, some recent neurosciences literature provides insights to why a few individuals are able to make major breakthroughs which are highly relevant to scientists in many fields (though most scientists work on relatively narrow problems in highly specialized fields).

Laboratories where Major Discoveries Occur

Critical to our research has been the definition of a major discovery. A major breakthrough or discovery is a finding or a process, often preceded by numerous ‘small advances’, which leads to a new way of thinking about a problem. This new way of thinking is highly useful in addressing problems confronted by numerous scientists in *diverse* fields of science.

In this definition, the emphasis on ‘diverse fields of science’ is critical. Not only was each of the 291 discoveries in our research highly relevant to scientists in separate fields of science, but the discoveries were made by scientists who internalized considerable scientific diversity, who tended to be boundary-crossers, and could communicate with scientists in multiple fields. Since a trend in twentieth-century science has been towards increasing specialization, it is significant that major discoveries have tended to be highly relevant to scientists in multiple scientific specialities and were made by scientists who were not highly specialized but by those who internalized considerable scientific diversity.

This strategy for defining a major discovery is quite different from the rare paradigm shifts which Thomas Kuhn analysed in *The Structure of Scientific Revolutions* (1962). Major breakthroughs about problems in basic biomedical science occur within paradigms about which Kuhn wrote. Historically, a major breakthrough in biomedical science was a radical or new idea, the development

Table 8.1 *Indicators of major discoveries*

1 Discoveries resulting in the Copley Medal, awarded since 1901 by the Royal Society of London, insofar as the award was for basic biomedical research.
2 Discoveries resulting in a Nobel Prize in Physiology or Medicine since the first award in 1901.
3 Discoveries resulting in a Nobel Prize in Chemistry since the first award in 1901, insofar as the research had high relevance to biomedical science.
4 Discoveries resulting in ten nominations in any three years prior to 1940 for a Nobel Prize in Physiology or Medicine.*
5 Discoveries resulting in ten nominations in any three years prior to 1940 for a Nobel Prize in Chemistry if the research had high relevance to biomedical science.*
6 Discoveries identified as prize-worthy for the Nobel Prize in Physiology or Medicine by the Karolinska Institute committee to study major discoveries and to propose Nobel Prize winners.*
7 Discoveries identified as prize-worthy for the Nobel Prize in Chemistry by the Royal Swedish Academy of Sciences committee to study major discoveries and to propose Nobel Prize winners.* These prize-worthy discoveries were included if the research had high relevance to biomedical science.
8 Discoveries resulting in the Arthur and Mary Lasker Prize for basic biomedical science.
9 Discoveries resulting in the Louisa Gross Horwitz Prize in basic biomedical science.
10 Discoveries resulting in the Crafoord Prize, awarded by the Royal Swedish Academy of Sciences, if the discovery had high relevance to the biological sciences.

[*] I have had access to the Nobel Archives for the Physiology or Medicine Prize at the Karolinska Institute and to the Archives at the Royal Swedish Academy of Sciences in Stockholm for the period from 1901 to 1940. I am most grateful to Ragnar Björk, who did most of the research in the Karolinska Institute's archives to identify major discoveries according to the indicators in this table. Because the archives are closed for the past 50 years for reasons of confidentiality, I have used other prizes (Crafoord, Lasker, Horwitz,) to identify major discoveries in the last several decades.

of a new methodology, or a new instrument or invention. It usually did not occur all at once, but involved a process of investigation taking place over a substantial period of time and required a great deal of tacit and/or local knowledge. My colleagues and I have chosen to depend on the scientific community to operationalize this definition, counting as major discoveries bodies of research meeting at least one of the ten criteria listed in Table 8.1.

We have studied in considerable detail all the laboratories where each of the 291 major discoveries occurred as defined in Table 8.1. Among other things, we have attempted to learn for each of the 291 discoveries where, when and by whom was the research done? What were the characteristics of the culture and the structure of the laboratory where the research occurred? [4]

We have also studied in detail the characteristics of a large number of laboratories headed by highly visible scientists (members of the Royal Society, the National Academy of Sciences, College de France, etc.) who never made major discoveries, in order to discern whether there were significant differences in the two populations of laboratories. After conducting our research on laboratories, we observed two general types of labs: those with significant scientific diversity, headed by lab directors who had the capacity to integrate the diversity in order to address problems relevant to numerous fields of science – in Table 8.2 we label these as Type A Labs. The other type of laboratories was much more narrow in scope and was more oriented to the issues involving a single discipline. These we label Type B labs (see discussion in Hollingsworth, 2006; Hollingsworth *et al*., 2008).

Table 8.2 *Two general types of laboratories in the basic biomedical sciences*

Characteristics of Type A Laboratories

1 Cognitive: High scientific diversity
2 Social: Well connected to invisible colleges (for example, networks) in diverse fields
3 Material Resources: Access to new instrumentation and funding for high-risk research
4 Personality of lab head: High cognitive complexity, high confidence and motivation
5 Leadership: Excellent grasp of ways that different scientific fields might be integrated and ability to move research in that direction

Characteristics of Type B Laboratories

1 Cognitive: Moderately low scientific diversity
2 Social: Well connected to invisible colleges (for example, networks) in a single discipline
3 Material Resources: Limited funding for high-risk research
4 Personality of lab head: Lack of high cognitive complexity, limited inclination to conduct high-risk research
5 Leadership: Not greatly concerned with integrating different scientific fields

Almost all the 291 discoveries in our project were made in Type A laboratories. However, all Type A laboratories did not succeed in making a major discovery. Indeed, most did not. As many scientists and others have observed, there is a certain amount of chance and luck in the making of major discoveries (Edelman, 1994: 980–86; Friedman, 2001; Jacob, 1995; Merton and Barber, 2004; Simonton, 1988: chapter Two; Zuckerman, 1977). Most of the scientists who headed Type A labs internalized considerable scientific diversity and had high cognitive complexity, whether they succeeded in making a major discovery or not.

Type B laboratories are at the opposite end of the continuum on virtually all the lab characteristics. Significantly, none of the 291 discoveries in our research occurred in Type B labs. The heads of Type B labs tended to be scientists who internalized much less scientific diversity and had lower levels of cognitive complexity than those who were the leaders in Type A laboratories.

The more Type A laboratories there have been in a single organization and the more they have had high interaction with each other across diverse fields, the greater the likelihood that the research organization has had multiple discoveries having a major impact on diverse fields of science. Figure 8.1 characterizes the conditions under which an organization might have multiple breakthroughs. The number of research organizations having these characteristics in basic biomedical science during the twentieth century were very few, however. The one organization which had more major breakthroughs (defined by criteria listed in Table 8.1) than any other throughout the twentieth century was the relatively small research organization in New York City, Rockefeller University (for an analysis of why that organization had so many Type A labs see Hollingsworth, 2004; Hollingsworth *et al.*, 2008). Because Type B labs have tended to focus on relatively narrow problems, they have also tended to have fewer rich interactions across diverse fields, and for this reason, organizations dominated by Type B labs have had few or no major discoveries.

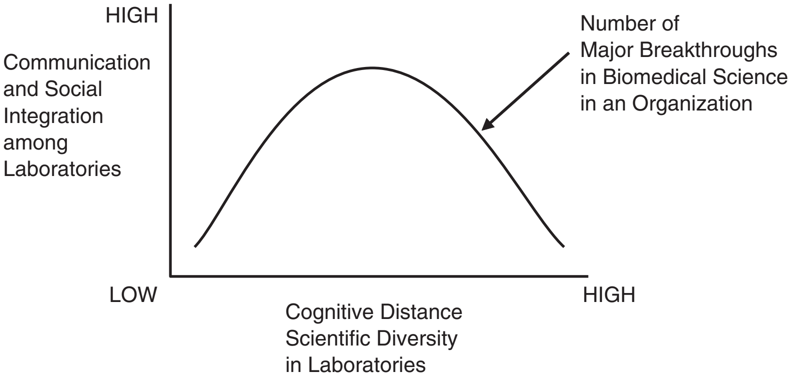

Figure 8.1 *The Relationship among Scientific Diversity, Communication/Integration and Making Major Discoveries.*

In our research, we have studied the institutional as well as the organizational context in which these labs were embedded. Variation in institutional environments leads to variation in the degree to which certain kinds of research organizations are dominant in a society. In sum, ours has been a multi-level analysis, concentrating on how institutional and organizational environments place constraints on how the types of labs and kinds of scientists are likely to be distributed across and within societies as well as across and within particular organizations within a society (Hollingsworth and Hollingsworth, 2000; Hollingsworth, 2004; 2006; Hollingsworth *et al.*, 2008). Others who have emphasized how the macro- and meso-environments of scientists have influenced innovativeness are Ben-David (1991), Cole and Cole (1973), Dogan and Pahre (1989), Merton (1973) and Zuckerman (1977). And while this essay also focuses on how these levels influence innovativeness, the distinctive argument of this essay is how those levels – combined with the social psychological features of scientists – influence the making of major discoveries.

High Cognitive Complexity and Major Discoveries

What is the relationship between high cognitive complexity and the making of major discoveries? The concept of cognitive complexity emerged some decades ago when research by psychologists failed to demonstrate that intelligence had much impact on individual performance. Because of their disappointment in being able to explain individual behaviour with various measures of intelligence, many psychologists began to focus their research on cognitive styles. Over time, cognitive complexity tended to be a better predictor of individual performance than measures of intelligence. The research on cognitive complexity suggests that cognitive traits of individuals tend to be stable over time, across subject areas and across tasks. There are numerous studies which suggest that individuals who have high cognitive complexity tend to be more tolerant of ambiguity, more comfortable not only with new findings but even with contradictory findings. Moreover, such individuals have a greater ability to observe the world in terms of grey rather than simply in terms of black and white. Psychologists have even defined a dimension of cognitive complexity with an emotional component: many with high cognitive complexity report that learning new things and moving into new areas is like play. They tend to be more intuitive and have a high degree of spontaneity in their thinking, to be individuals who enjoy exploring uncertainty and engaging in high-risk research rather than working in areas which are already well understood (Cacioppo *et al.*, 1996; Suedfeld, 2000). Moreover, cognitive complexity as a variable has been useful in helping to explain how individual scientists interact with their institutional and organizational environments (Grigorenko, 2000: 165; Grigorenko and Sternberg, 1995; Sternberg, 1997; Wardell and Royce, 1978).

Our data on scientists over the past century who have had high cognitive complexity and made major discoveries suggest that there are distinct social and psychological processes which influence the emergence of high cognitive complexity. We have derived our data from many different sources. We interviewed more than 450 scientists in the four countries and have worked in numerous archives containing correspondence and papers of scientists associated with making major discoveries. In addition, we have studied large numbers of biographies, autobiographies and obituaries of individuals, both those who made and did not make major discoveries. Because I wish to study the scientists who made major discoveries over a century, obviously I do not rely heavily on the kind of contemporary data which clinical psychologists normally use. Rather, much of the data are historical in nature.

Cognitive complexity tends to have its roots in various social psychological processes. Here I present two processes which were particularly notable in enhancing the cognitive complexity of high achieving scientists: the internalization of multiple cultures and having non-scientific avocations. The essay argues that distinguished scientific achievement results from the internalization of scientific diversity, but it is cognitive complexity which facilitates scientific diversity and high scientific achievement.

Internalizing Multiple Cultures

A very high proportion of those who have high cognitive complexity internalize multiple cultures in very meaningful ways. However, there are numerous pathways by which one might internalize multiple cultures. Indeed, the defining of multiple cultures is not an easy task. At the most elementary level, an individual who internalizes multiple identities, each of which is defined by cultural traits, necessarily internalizes multiple cultures, and this facilitates the capacity of such an individual to observe the world in more complex terms than the individual who internalizes much less cultural diversity.

A common explanation as to why individuals have high cognitive complexity is because they have internalized multiple cultures based on ethnicity, nationality and/or religion (Hage and Powers, 1992). To acquire multiple cultural identities, it is not sufficient to live in a world where one is simply exposed to multiple cultures. Rather one must be sufficiently socialized by multiple cultures so that one actually internalizes the norms, habits and conventions of more than one culture. Such an individual then literally has the capacity to live intuitively in multiple worlds simultaneously. The argument here is that such an individual has the ability to observe the world in more complex terms and has the potential to be more innovative than those who internalize less cultural diversity.

There is an extensive literature pointing to the high achievements of German–Jewish scientists in the first-third of the twentieth century, achievements quite out of proportion to the Jewish fraction of the German population. A common explanation in the literature has been the emphasis which Jewish families placed on formal learning (Nachmansohn, 1979). This may be an important part of the explanation, but we need to broaden this perspective, for there were numerous non-Jewish scientists of high distinction who also internalized multiple cultures: some who were part Polish and part French, some had one parent who was Catholic and another who was Protestant, some had one parent who was French and another North African, some who internalized Latin American and British cultures and so forth. Because such individuals lived in intimate association with multiple worlds, they tended to have weak identities with each and for this reason they could more clearly perceive the world with a certain detachment, to have a higher level of cognitive complexity, and to have the potential to develop novel or creative views of the world.

The scientists in our population who internalized multiple cultures tended to be both insiders and outsiders, and it was this capacity to live in more than one world simultaneously that was the key to having high cognitive complexity. When they attended universities, it was almost second nature to cross from one field into another, to be both an insider and outsider. Just as in their personal lives they internalized multiple cultures, in their scientific lives they also internalized scientific diversity. And it is no accident that in this age of specialization, the discoveries by these scientists reflected a great deal of scientific diversity. Indeed, one of their key traits was the capacity to see and understand relations among multiple fields. From our population of scientists who made major discoveries in basic biomedical science as well as from the lives of many other scientists in the twentieth century, the capacity to internalize scientific diversity was virtually universal.

As suggested above, many observers have long been aware that some of the most renowned scientists of the twentieth century were Jewish. Within my population of scientists who internalized multiple cultures and who made major discoveries in the basic biomedical sciences were such well-known Jewish scientists as the following: Gerald Edelman, Fritz Haber, Roald Hoffmann, Francois Jacob, Aaron Klug, Hans Krebs, Karl Landsteiner, Rita Levi-Montalcini, Jacques Loeb, Andre Lwoff, Elie Metchnikoff, Otto Meyerhoff, Max Perutz and Otto Warburg. In my investigations of basic biomedical scientists who made major discoveries, I became increasingly interested in those who internalized multiple cultures so I could better understand some of the determinants of high cognitive complexity. I first focused on Jews who made major discoveries in basic biomedical science, as in our interviews and other investigations it became quite obvious that many of these were individuals who not only had high cognitive complexity but also internalized multiple cultures. Interestingly, the number of Jews in the population proved to be far greater than my colleagues and I originally suspected. Because of the very large number of Jews associated with major discoveries in basic biomedical science and closely related fields, I present their names in Table 8.3.

Table 8.3 *Jewish scientists who made major discoveries in basic biomedical and related sciences 1901–2005*[5]

Part One: Jewish Scientists Awarded Nobel Prizes in Physiology or Medicine

Paul Ehrlich (1908)
Elie Metchnikoff (1908)
Robert Bárány (1914)
Otto Meyerhof (1922)
Karl Landsteiner (1930)
Otto Warburg (1931)
Otto Loewi (1936)
Joseph Erlanger (1944)
Herbert Gasser (1944)
Sir Ernst Chain (1945)
Hermann Muller (1946)
Gerty Cori (1947)
Tadeus Reichstein (1950)
Selman Waksman (1952)
Sir Hans Krebs (1953)
Fritz Lipmann (1953)
Joshua Lederberg (1958)
Arthur Kornberg (1959)
Konrad Bloch (1964)
Francois Jacob (1965)
André Lwoff (1965)
George Wald (1967)
Marshall Nirenberg (1968)
Salvador Luria (1969)
Julius Axelrod (1970)
Sir Bernard Katz (1970)
Gerald Edelman (1972)
David Baltimore (1975)
Howard Temin (1975)
Baruch Blumberg (1976)
Andrew Schally (1977)
Rosalyn Yalow (1977)
Daniel Nathans (1978)
Baruj Benacerraf (1980)
Sir John Vane (1982)
César Milstein (1984)
Michael Brown (1985)
Joseph Goldstein (1985)
Stanley Cohen (1986)
Rita Levi-Montalcini (1986)
Gertrude Elion (1988)
Harold Varmus (1989)
Edmond Fischer (1992)
Alfred Gilman (1994)
Martin Rodbell (1994)
Stanley Prusiner (1997)
Robert Furchgott (1998)
Paul Greengard (2000)
Eric Kandel (2000)
Sydney Brenner (2002)
H. Robert Horvitz (2002)
Richard Axel (2004)

Part Two: Jewish Scientist Awarded Nobel Prizes in Areas of Chemistry Relevant to Basic Biomedical Science

Adolph von Baeyer (1905)
Henri Moissan (1906)
Otto Wallach (1910)
Richard Willstätter (1915)
Fritz Haber (1918)
George de Hevesy (1943)
Melvin Calvin (1961)
Max Perutz (1962)
Christian Anfinsen (1972)
William Stein (1972)
Ilya Prigogine (1977)
Herbert Brown (1979)
Paul Berg (1980)
Walter Gilbert (1980)
Roald Hoffmann (1981)
Aaron Klug (1982)
Herbert Hauptman (1985)
Jerome Karle (1985)
John Polanyi (1986)
Sidney Altman (1989)
Rudolph Marcus (1992)
George Olah (1994)
Harold Kroto (1996)
Walter Kohn (1998)
Alan Heeger (2000)
Aaron Ciechanover (2004)
Avram Hershko (2004)
Irwin Rose (2004)

Part Three: Jewish Scientists Awarded the Lasker Award in Basic Biomedical Science

Selman Waksman (1948)
Sir Hans Krebs (1953)
Michael Heidelberger (1953)
George Wald (1953)
Theodore Puck (1958)
Heinz Fraenkel-Conrat (1958)
Jules Freund (1959)
Harry Rubin (1964)
Bernard Brodie (1967)
Marshall Nirenberg (1968)
Seymour Benzer (1971)
Sydney Brenner (1971)
Charles Yanofsky (1971)
Ludwik Gross (1974)
Sol Spiegelman (1974)
Howard Temin (1974)
Andrew Schally (1975)
Rosalyn Yalow (1976)
Sir John Vane (1977)
Hans Kosterlitz (1978)
Solomon Snyder (1978)
Walter Gilbert (1979)
Paul Berg (1980)
Stanley N. Cohen (1980)
Harold Varmus (1982)
Eric Kandel (1983)
César Milstein (1984)
Michael Brown (1985)
Joseph Goldstein (1985)
Rita Levi-Montalcini (1986)
Stanley Cohen (1986)
Philip Leder (1987)
Alfred Gilman (1989)
Stanley Prusiner (1994)
Jack Strominger (1995)
Robert Furchgott (1996)
Mark Ptashne (1997)
Aaron Ciechanover (2000)
Avram Hershko (2000)
Alexander Varshavsky (2000)
James Rothman (2002)
Randy Schekman (2002)

Part Four: Jewish Scientist Awarded the Louisa Gross Horwitz Prize

Marshall Nirenberg (1968)
Salvador Luria (1969)
Harry Eagle (1973)
Theodore Puck (1973)
Boris Ephrussi (1974)
Seymour Benzer (1976)
Charles Yanofsky (1976)
Michael Heidelberger (1977)
Elvin Kabat (1977)
Walter Gilbert (1979)
César Milstein (1980)
Aaron Klug (1981)
Stanley Cohen (1983)
Viktor Hamburger (1983)
Rita Levi-Montalcini (1983)
Michael Brown (1984)
Joseph Goldstein (1984)
Mark Ptashne (1985)
Alfred Gilman (1989)
Stephen Harrison (1990)
Michael Rossmann (1990)
Stanley Prusiner (1997)
Arnold Levine (1998)
Bert Vogelstein (1998)
H. Robert Horvitz (2000)
Avram Hershko (2001)
Alexander Varshavsky (2001)
James Rothman (2002)
Randy Schekman (2002)
Ada Yonath (2005)

Sources: JINFO, 2005a,b,c,d and e

The list in Table 8.3 identifies scientists as being Jewish in a number of different ways. In a very strict sense, there is no single definition of a Jew. All who are listed in Table 8.3 had some identity as being Jewish even if they were not Jewish in a religious sense, or did not associate with others who were Jewish. Indeed, some disguised their Jewish origins and married non-Jewish spouses. Some were extraordinarily secular or even atheist. In Table 8.3 we list high-achieving scientists in our population if their Jewish background – however defined – contributed to their (1) having some awareness of being Jewish and (2) contributed to their internalization of multiple cultures and having high cognitive complexity (Weisskopf, 1991: 27; also See Nachmansohn, 1979; Stoltzenberg, 1994).[6]

How a Jewish background worked out was very complex and varied from person to person and from society to society. Many were marginal to the society in which they grew up. Some like Nobel laureate Gertrude Elion were essentially ‘multiple outsiders’. Her father had arrived in the United States from Lithuania and had descended from a line of rabbis who have been traced through synagogue records to the year 700. Her mother had emigrated from a part of Russia that is now part of Poland and her grandfather had been a high priest. Gertrude’s maternal grandfather who had the greatest influence on her, was a learned biblical scholar who was fluent in several languages, and for years Gertrude and her grandfather spoke Yiddish together. But Gertrude as a young girl realized that she wanted to be a scientist – a man’s profession. Hence, she not only internalized the culture of being Jewish and American, but also being a woman in an occupation dominated by men (Interview with Elion; McGrayne, 1993: 280–303).

Rosalyn Yalow was another Nobel laureate whose early life was being both insider and outsider. Her Jewish parents were immigrants to the United States who had little formal education, but they strongly encouraged her education. Hence during Yalow’s early years, she tended to live in two separate worlds: one in which she received much encouragement from her uneducated immigrant parents and another in the public schools of the South Bronx. Later, she became very interested in physics, a male-dominated world. Again, she was an outsider. Fortunately for her, when she began graduate work during the Second World War there were not enough male graduate students to be research and teaching assistants. As a result, she was accepted in the Physics Department of the University of Illinois and given a stipend. Subsequently, she began to work with a group of physicians in the Bronx Veterans Administration hospital, but as a physicist she was again an outsider. It was as a result of this dual role of being both insider and outsider that she was able to establish bridges between the world of physics and medicine and to be one of the few scientists in the developing field of nuclear medicine (Csikszentmihalyi, 1996: 192–96; Howes, 1991: 1283–91; McGrayne, 1993: 333–55; Opfell, 1978).

As the sociologist Robert Park (1937: xvii–xxiii) observed many years ago, the marginal person is often a personality type who emerges where different cultures come into existence, and such an individual often assumes both the role of the cosmopolitan and the stranger. Because such an individual internalizes multiple cultures, he/she has the potential to develop a wider horizon, a keener intelligence, a more detached and rational viewpoint – the ingredients of a creative person (Park, 1937: xvii–xxiii). Somewhat earlier, the German sociologist Georg Simmel (1908) had developed similar ideas about the perceptiveness and potential innovativeness of the individual who is both insider and outsider (also see Dogan and Pahre, 1989; 1990). The psychologist Mihaly Csikszentmihalyi (1996: 177–78), a leading writer on creativity, has reminded us that there were also many routes by which high-achieving individuals have felt marginalized. Some experienced the life of the marginal individual because of their early success. Because they were so precocious, Nobel laureates John Bardeen, Manfred Eigen and Rosalyn Yalow were promoted to higher grades in school whereupon they were surrounded by older students with whom they were unable to establish any rapport.

Csikszentmihalyi (1996: 267) further suggests that many scientists have overcompensated for their marginalization with a relentless drive to achieve success, determination based on sacrifice, and discipline, but at the same time a fascination with constant learning about novel things. The American biologist E. O. Wilson, who experienced a painful childhood which generated a great deal of personal insecurity, has suggested that all great scientists must be marginal at times in their career. He too felt marginalized at moments in his highly successful and fascinating career (Wilson, 1994). According to Wilson, being a highly successful scientist requires ‘enormous amounts of work and pain. And you have to accept a certain amount of rejection. [. . .] You have to be ignored for periods of time’ (quoted by Csikszentmihalyi, 1996: 269; interviews with Wilson).

As the above paragraphs suggest, the emergence of multiple ethnic and national identities was not the only path for internalizing multiple cultures. Some scientists in our population internalized multiple identities or cultures by living simultaneously in two social worlds based on social class. For example, Sir James Black who was awarded the Nobel Prize in Physiology or Medicine in 1988 came from a relatively rural coal-mining community. He came from an upper-middle-class family in which his father was a mining engineer and colliery manager, but Black’s peers were children of coal miners. In short, Black was living and negotiating in two different worlds – that of his professionally oriented home and that of the coal mining community where there was extremely high distrust of the mining management. Significantly, Black's tendency to live in two worlds concurrently has continued throughout his life: his scientific career was that of one living in multiple worlds, crossing boundaries and integrating in his own mind that which most of his scientific colleagues would never have been able to do (Black, 1988; interview with Black).

A similar case involved that of Gobind Khorana who was awarded the Nobel Prize in Physiology or Medicine in 1968. Khorana's cultural diversity was also derived from living in a small village in India, where his father was a civil servant and his family was the only one who could read English. In fact, most villagers had difficulty even in understanding English. Thus, Khorana grew up internalizing both the cultural world of the village and the more cosmopolitan world of his parents, and from this dual environment he was socialized to be both an insider and outsider, to be a boundary crosser – traits which facilitated his understanding relationships among multiple fields of science and making a major discovery.

Another case with a similar theme was that of Jacques Monod who was awarded the Nobel Prize for Physiology or Medicine in 1965. Monod also spent his childhood in multiple cultural worlds. His father was from a Protestant Huguenot family in Catholic France, while his mother was an American from Milwaukee and Iowa. His father was a painter who was an avid reader of science. This kind of socialization into a world of cultural diversity led to Monod's becoming a classical man of opposites, both an insider and outsider: growing up in a rigid Protestant culture but in a Catholic society, a man who was highly emotional but who insisted on great scientific precision, a man very musically oriented with democratic values but autocratic in his behaviour, a scientist who was able to integrate the best in both French and American styles of science.

There was the well-known case of Peter Medawar who was born in Brazil of a Lebanese father and an English mother. From there he was eventually sent to an English public school – Marlborough – and later became a student at Magdalen College, Oxford. Medawar indeed internalized an amazing amount of cultural diversity and this proved to be an enormous asset to him as he became a boundary-crosser in various scientific fields.

Another woman who excelled in the male-dominated world of science was Irène Joliot-Curie, awarded the Nobel Prize in Chemistry in 1935 with her husband Frédéric Joliot. A major factor in her ability to bring together disparate trends in chemistry and physics was her high cognitive complexity which was very much influenced by the cultural diversity she internalized. Irène was the daughter of Polish-born Nobel laureate Marie (Sklodowska) Curie and French-born Nobel laureate Pierre Curie. Irène grew up in Paris, but under the supervision of a Polish governess who spoke Polish to her on a daily basis. Irène also came under the strong influence of her French paternal grandfather who was very anticlerical in a culture under the dominance of the Catholic Church. While her peers attended the rather rigid schools operated by the French state, Irène attended a private cooperative school and was tutored in mathematics by her mother. In short, as a young girl she was intimately socialized to live in multiple worlds simultaneously (McGrayne, 1993: 11–36, 117–43).

Many individuals emerged from a multicultural world but never internalized in a deep sense the cultural diversity of their environment. All other things being equal, the greater the cultural diversity within a social space, the greater the likelihood that an individual will internalize multiple cultures and have potential to be highly innovative. However, there are many qualifications which must be made to such a generalization. The more structural and cultural barriers among those of different cultural backgrounds and the less the access to leading centres of learning, the lower the likelihood that individuals in a multicultural society will internalize cultural diversity. Hence, across multicultural environments there is variation in the degree to which individuals will internalize multiple cultures. Poland and Germany in the first third of the twentieth century were multicultural societies, but Polish Jews faced greater cultural and structural obstacles to scientific institutions than German Jews did. Even though anti-Semitism existed in both societies, it was more intense in Poland than in Germany, and partly for that reason, Polish Jews were less able to internalize cultural diversity and to be as innovative as German Jews at the same time.[7] This difference explains in part differences between the two populations in achievement of major breakthroughs in science in the first third of the twentieth century.

The United States is a multicultural society where many have internalized multiple cultures, and this has contributed to there being so many scientists in the United States who made major discoveries during the past century. A major exception involves African Americans. The extremely harsh experience of slavery and the intense racism throughout the twentieth century caused most African Americans to develop strong identities, but strong racial prejudice against them has made it very difficult historically to internalize in a very deep sense multiple ethnic or cultural identities. Because African Americans were long denied access to leading educational institutions, they were not as successful as Jewish Americans or other ethnic groups in making major discoveries. Indeed, the experience of African Americans suggests that if there is oppression and very strong discrimination against an ethnic group – even in a multicultural society – members of that group are unlikely to have the same levels of scientific achievement as those who internalize in a very deep way more than one culture. Because a number of indicators show racial oppression is diminishing in American society many more African Americans may come to internalize multiple cultures, and thus be more likely to be scientists of considerable distinction and achievement.

The Contributions of Avocations to High Cognitive Complexity

The basic argument of this essay is that the wider the range of experience and knowledge of the scientist, the more fields of science his/her work are likely to influence and the greater the importance with which it will be perceived (Csikszentmihalyi, 1996; Pelz and Andrews, 1966; Sternberg, 1988; Sternberg and Davidson, 1995). Thus far, the argument has been that cognitive complexity due to the internalization of multiple identities tends to enhance scientific diversity and scientific achievement. Cognitive complexity is further enhanced in those who already internalize considerable cultural diversity by engaging in mentally intensive avocations.

On the other hand, many scientists who did not internalize multiple cultures added to their cognitive complexity by mentally intensive engagement in avocations which on the surface did not appear to be related to their scientific work. On the basis of in-depth interviews (and from my study of biographical and rich archival materials), many scientists have made it abundantly clear that their avocations enriched the complexity of their minds and that many of their scientific insights were derived by engaging in what often appeared to be non-scientific activities. Impressive work in this area has been done by the Root-Bernsteins (1989; 1999) who argue that the skills associated with artistic and humanistic expression have positive effects in the conduct of scientific research. They contend that scientific accomplishments are enhanced by the capacity to be high-achieving in multiple fields – scientific as well as non-scientific – and by having the opportunity and ability to make use in science of skills, insights, ideas, analogies and metaphors derived from non-scientific fields. Many scientists have commented about the intuitive and non-logical factors in the act of discovery (Jacob, 1995; Medawar, 1991). Others have emphasized that the arts and humanities have the potential to stimulate the senses of hearing, seeing, smelling – enhancing the capacity to know and feel things 'in a multi-model, synthetic way' (Root-Bernstein, 2001: 65). Thus Einstein frequently observed that his theory of relativity occurred by intuition, but music was 'the driving force behind the intuition [...]. My new discovery is the result of musical perception' (Suzuki, 1969). Einstein's son observed of his father that '[w]henever he had come to the end of the road or into a difficult situation in his work, he would take refuge in music, and that would usually resolve all his difficulties' (Clark, 1971: 106). Root-Bernstein goes so far as to argue that 'no one with monomaniacal interests or limited to a single talent or skill can [...] be creative, since nothing novel or worthy can emerge without making surprising links between things [...]. To create is to combine, to connect, to analogize, to link, and to transform.' (2001: 66).

If fundamental discoveries are derived from experiencing unexpected connections from disparate fields and if discovery often has a strong emotional and intuitive quality to it, we should expect that many of the scientists in our population who were recognized for making major discoveries were also individuals who were quite accomplished performers in areas other than the scientific field for which they were renowned. There is indeed a very rich body of data revealing that highly recognized scientists in many fields were quite talented as writers, musicians, painters, sculptors, novelists, essayists, philosophers and historians. A number were also engaged in political activities – both closely and distantly related to their scientific activities. In Table 8.4, we list numerous scientists who made major accomplishments in the basic biomedical sciences who were also quite accomplished in various artistic and humanistic activities. While rather extensive, the list is probably an understatement. My colleagues and I still have incomplete data about the avocations of scientists who are in our population for being nominated for Nobel Prizes ten times in three different years but who never received a major prize for their achievement. Unfortunately, all of these 'ten-in-three' scientists are deceased, and the published materials about them is quite limited. We suspect that if we had had the same kind of extensive published materials on all of them as we do on those who received Nobel Prizes and other major prizes, we would have learned that most of the 'ten-in-three' scientists would also have been very talented in various avocational fields.

Table 8.4 *Twentieth-century scientists who made major discoveries and were also quite active in music, art, writing, crafts and politics*[8]

Musicians			
Luis Alvarez*	Physicist	Otto Meyerhof*	Biologist
Clay Armstrong*	Biologist	Albert A. Michelson*	Physicist
Oswald T. Avery*	Microbiologist	Jacques Monod*	Biologist
Georg von Békésy*	Physiologist	Rolf Nevanlinna	Mathematician
Walter B. Cannon#	Physiologist	Wilhelm Ostwald*	Physical Chemist
Ernst Chain*	Chemist	Max Planck*	Physicist
Louis De Broglie*	Physicist	Ilya Prigogine*	Physicist
Gerald Edelman*	Biologist	Mark Ptashne*	Biologist
Manfred Eigen*	Chemist	Ronald Ross*	Biologist
Albert Einstein*	Physicist	Solomon Snyder*	Biologist
Richard Feynman*	Physicist	Arnold Sommerfeld	Physicist
Otto Frisch	Physicist	Charles Stevens	Biologist
Michael Heidelberger#	Chemist	Joseph J. Sylvester	Mathematician
Werner Heisenberg*	Physicist	Axel Hugo Theorell*	Physiologist
Gerhard Herzberg*	Chemist	Georges Urbain	Physicist
William Lipscomb*	Chemist	Paul Urban	Physicist
Jacques Loeb#	Biologist	J.H. Van't Hoff*	Physical Chemist
Barbara McClintock*	Physicist	Emil Warburg*	Biologist/Chemist
Ernst Mach	Geneticist	Victor Weisskopf	Physicist
Lise Meitner	Physicist	Edmund B. Wilson	Biologist
Composers of Music			
Albert A. Michelson*	Physicist	Walter Thirring	Physicist
Ronald Ross*	Biologist	Georges Urbain	Chemist
Poets			
Marie Curie*	Physical Chemist	William Ramsay*	Physical Chemist
Fritz Haber*	Chemist	Charles Richet*	Physiologist
Otto Hahn*	Physical Chemist	Ronald Ross*	Biologist
A.V. Hill*	Biologist	Erwin Schrödinger*	Physicist
Roald Hoffmann*	Chemist	Charles Sherrington*	Physiologist
Otto Meyerhof*	Biologist	J. H. Van't Hoff*	Physical Chemist
S.H. Mueller	Mathematician	Selman A. Waksman*	Bacteriologist
H.J. Muller*	Geneticist	Richard Willstätter*	Chemist
Walther Nernst*	Physical Chemist		
Dramatists			
Fritz Haber*	Chemist	Charles Richet*	Physiologist

Novelists			
Carl Djerassi	Chemist	Charles Richet*	Physiologist
Fred Hoyle	Astrophysicist	Norbert Wiener	Cyberneticist
Painters and Sketchers			
Edgar Adrian*	Physiologist	Howard Florey*	Chemist
Frederick Banting*	Physiologist	Roger Guillemin*	Physiologist
Joseph Barcroft[#]	Physiologist	Cyril Hinshelwood*	Physical Chemist
Theodor Boveri*	Biologist	Dorothy Hodgkin*	Chemist
Lawrence Bragg*	Physicist	Joseph Lister[#]	Physician
William Bragg*	Physicist	Otto Loewi*	Physiologist
Ernst Brücke	Physiologist	Konrad Lorenz*	Ethologist
S. Ramon y Cajal*	Neuroanatomist	Wilhelm Ostwald*	Physical Chemist
Harvey Cushing[#]	Surgeon	Louis Pasteur	Biologist
H. von Euler-Chelpin*	Biochemist	E.A. Scharpey-Schaefer*	Physiologist
Richard Feynman*	Physicist	Nico Tinbergen*	Biologist
Alexander Fleming*	Bacteriologist	E. O. Wilson*	Biologist
Sculptors			
Robert Holley*	Biochemist	Roger Sperry*	Biologist
Salvadore Luria*	Biologist	Georges Urbain	Physicist
Drafters			
Luis Alvarez*	Physicist	Linus Pauling*	Physical Chemist
George Beadle*	Biologist	William Ramsay*	Physical Chemist
Involved in Architecture			
Gunter Blöbel*	Biologist	Peter Mitchell*	Biologist
Otto Hahn*	Chemist	Robert G. Roeder*	Biologist
Photographers			
Patrick Blackett*	Physicist	Wilhelm Ostwald*	Physical Chemist
S. Ramon y Cajal*	Neuroanatomist	Wilhelm Roentgen*	Physicist
Gertrude Elion*	Biochemist	Ernest Rutherford*	Physicist
Howard Florey*	Chemist	E.A. Sharpey-Schaefer*	Physician
Tim Hunt*	Biochemist	Nico Tinbergen*	Biologist
Robert Koch*	Bacteriologist	Charles T.R. Wilson*	Physicist
Gabriel Lippman*	Physicist		
Woodworkers or Metalworkers			
Luis Alvarez*	Physicist	Walter Rudolf Hess*	Biologist
Joseph Barcroft*	Physiologist	Andrew Huxley*	Biologist
William Bayliss*	Physiologist	Barbara McClintock*	Geneticist
Georg von Békésy*	Physiologist	Wilhelm Ostwald*	Physical Chemist
Walter Cannon[#]	Physiologist	Louis Pasteur	Physician/Immunologist
Gerald Edelman*	Biologist	William Ramsay*	Physical Chemist
J. Willard Gibbs	Physicist	Theodor Svedberg*	Physical Chemist
Scientists who Wrote Philosophy, History, Anthropology and/or Popular Science			
Paul Berg*	Biologist	Frances Crick*	Biologist/Physicist
Baruch Blumberg*	Biologist	Richard Dawkins	Biologist/Ethologist
Niels Bohr*	Physicist	John Eccles*	Biologist
Pierre Broca	Biologist	Gerald Edelman*	Biologist
S. Ramon y Cajal*	Biologist	Manfred Eigen*	Chemist
Alexis Carrel*	Biologist	Albert Einstein*	Physicist
Erwin Chargaff	Biochemist	Richard Feyman*	Physicist
Andre Cournand*	Biologist	Simon Flexner[#]	Physician/Psychiatrist

(*Continued*)

Table 8.4 *Continued*

Sigmund Freud[#]	Biologist	Jacques Monod*	Biologist
Murray Gell-Mann*	Physicist	Wilhelm Ostwald*	Physical Chemist
Stephen J. Gould	Biologist	Max Perutz*	Chemist
Stephen Hawking	Physicist	Max Planck*	Physicist
Werner Heisenberg*	Physicist	Henri Poincaré	Mathematician
J.H. Van't Hoff*	Chemist	Michael Polanyi	Chemist
Fred Hoyle	Astrophysicist	Ilya Prigogine*	Physicist
Francois Jacob*	Biologist	S. Ramon y Cajal*	Biologist
Eric Kandel*	Biologist	Martin Rees	Cosmologist
Hans Krebs*	Biochemist	Peyton Rous*	Biologist
M.T.F. von Laue*	Physicist	Oliver Sacks	Neurologist
Joshua Lederberg*	Biologist	Carl Sagan	Astronomer
Richard Lewontin	Biologist	Erwin Schrödinger*	Physicist
Ernst Mach	Physicist	Charles Sherrington*	Physiologist
Ernst Mayr*	Biologist	Nikolaas Tinbergen*	Biologist/Ethologist
Peter Medawar*	Biologist	James D. Watson*	Biologist
Otto Meyerhof*	Biologist	Steven Weinberg*	Physicist
Robert Millikan*	Physicist	E. O. Wilson*	Biologist
Political Activists			
Patrick Blackett*	Physicist	Salvador Luria*	Biologist
Niels Bohr*	Physicist	Matthew Meselson	Biologist
John Desmond Bernal	Physicist	Jacques Monod*	Biologist
John Cockcroft*	Physicist	Nevill Mott*	Physicist
Paul Doty	Chemist	Robert Oppenheimer	Physicist
Albert Einstein*	Physicist	Linus Pauling*	Physical Chemist
James Franck*	Physicist	John Polanyi*	Chemist
Archibald Vivian Hill*	Biologist	Ronald Ross*	Biologist/Physician
Dorothy Crowfoot Hodgkin*	Chemist	Abdus Salam*	Physicist
Frédéric Joliot-Curie*	Chemist	Richard Synge*	Chemist
Irene Joliot-Curie*	Chemist	Leo Szilard	Physicist
Robert Koch*	Biologist	Edward Teller	Physicist
Joshua Lederberg*	Biologist	James D. Watson*	Biologist
Hendrik Antoon Lorentz*	Physicist	Victor Weisskopf	Physicist

Legend:
* Received Nobel, Lasker, Horwitz and/or Crafoord Prize and/or Copley Medal.
[#] Scientists whose discoveries resulted in ten nominations in three different years prior to 1940 for a Nobel Prize in Physiology or Medicine or in Chemistry if the research had high relevance to biomedical science.

The thesis of this essay is not that all scientists having high cognitive complexity made major discoveries. Rather, its main argument is that those with high cognitive complexity – for whatever reason – tended to have qualitatively different styles of doing science than those who did not have high cognitive complexity. The greater their cognitive complexity – whether as a result of internalizing multiple cultures and/or from participating in various artistic and humanistic fields – the greater the likelihood that they would be highly achieving scientists.

For many scientists, their activities as an artist, painter, musician, poet, etc., enhanced their skills in pattern formation and pattern recognition, skills that they could transfer back and forth between science and art. It was part of their ability to understand reality in more than one way. The great chemist Robert Woodward and many others marvelled at how their activities as artists reinforced their abilities to recognize complex patterns in nature. Roald Hoffmann, a Nobel laureate in chemistry who is also a poet, argues vigorously that scientists have no more 'insight into the workings of nature than poets'. Hoffmann's science describes nature with equations and chemical structures but he argues that his science is an incomplete description. By using ordinary language to describe nature, Hoffmann believes he has a richer understanding of the world. In short, the more different ways we can describe reality, the richer our description and understanding. For Hoffmann (1981; 1995) and many others, the roles of artist and scientist are mutually reinforcing. The physicist Victor Weisskopf in his autobiography (1991: chapter 14) makes a powerful argument that artistic and scientific activities complement one another in the mind of the scientist. Both are needed in order to have a more complete understanding of the world.[9]

Perspectives from Neuroscience and the Making of Major Discoveries

Thus far we have suggested that individuals who internalize multiple cultures and who have well-developed aesthetic interests will tend to have high cognitive complexity, enhancing their ability to understand the interconnectedness and relations among different phenomena. It is this ability to understand complex relations among things which is key to the ability to generate novel views about phenomena (Simonton, 1988). In short, internalizing multiple cultures and being highly engaged in mentally intense activities outside of science increase the likelihood that individuals will make major discoveries. In addition, our data suggest that being in organizational environments with other individuals who also internalize cultural and scientific diversity enhances the likelihood of making major discoveries (Hollingsworth, 2004). But organizational factors are not necessary or sufficient conditions for the making of a major discovery. Rather, these factors increase the probability of making a major discovery (Hollingsworth and Hollingsworth, 2000; Hollingsworth, 2004).

Neuroscientists and cognitive psychologists have long been concerned with the consequences of complex experiences for behaviour. The perspectives presented here are somewhat complementary with some of those which have emerged in the fields of neuroscience and cognitive psychology. To make the argument about high cognitive complexity and major discoveries more comprehensible, it may be helpful to relate cognitive complexity as discussed here to some of the views suggested by literature in neuroscience and cognitive psychology.

If internalizing multiple cultures leads to high cognitive complexity, perhaps we should ask why children in the same family or a similar social environment vary greatly in their cognitive complexity. This is not an easy problem to confront. Some sociologists and psychologists have long been intrigued with the fact that there is great variation in the performance of siblings and others raised in the same structural and cultural environment. Jencks *et al.* (1972) reported with a large sample of the American population that there is just as much variation in occupational attainment and income among siblings in the same family as in the population at large. Moreover, there is substantial literature which demonstrates that variation in the birth order of children within the same family leads to important differences in their behaviour, abilities and careers (Sulloway, 1996).[10]

Some neuroscience literature is suggestive for the problem of why children reared in the same family vary so much in their behaviour, and why different children growing up in the same multicultural environment may vary enormously in the degree to which they internalize cultural diversity and have high cognitive complexity. The starting point of this literature is that every brain is unique and distinctive. Nobel laureate Gerald Edelman and others inform us that even the brains, thoughts, emotions and levels of consciousness among identical twins raised in the same family are different (Edelman, 1987; 1989; 1992; 2004; Edelman and Gally, 2001; Edelman and Tononi, 2000; McGraw, 1935).

Each mind is made up of millions of neurons connected to neighbouring neurons across synapses, and the number and complexity of these connective patterns is almost unlimited. Within the cerebral cortex alone, there are approximately 10 billion neurons. If one were to count all the connections of neurons by synapses – one per second – one would finish counting them about 32 million years after one began (Edelman, 1992: 17). It is through extraordinarily complex sensory experiences that connections are generated among neurons. Throughout the life of the individual, each perception is modified by a person's genetic structure as well as by previous sensory experiences and connections. Each mind is constantly making complex classifications of phenomena related to previous sensory experiences. It is through the thickness of connections and in the almost limitless complexity and variety of experiences that the brain is able to detect patterns and to develop abstract relations among different phenomena. As a result of the billions and billions of different sensory experiences of individuals, each person – even when exposed to the same circumstances – codes or responds to the same observations or phenomena differently (Dempsey, 1996; Edelman, 1987; 1989; 1992; Hayek, 1952). As McGraw (1935) and others (Dalton, 2002: chapters 9 and 10) have demonstrated, this variation begins very early in the development of an individual. It is for this reason that even if several children in the same family are exposed to a similar multicultural environment, only one child may internalize a high level of cultural diversity and have high cognitive complexity.

Every new experience is influenced by all previous experiences. In short, the human mind is highly path-dependent (Rizzello, 1997; 2003). The synaptic reorganizations within the brain are continuously occurring with such enormous complexity that each individual perceives the world in a unique way. The mind with high cognitive complexity has a larger repertoire of patterns ready to be applied to the perception of each new situation.

One way that the uniqueness of each mind is revealed is in the connections among multiple parts of each brain. In each individual, every experience is related to all other experiences and each is mutually reinforcing (Dempsey, 1996; Hayek, 1952). There is no disjuncture between the end of one experience and the beginning of another. But each new experience has an effect on the entire mind.

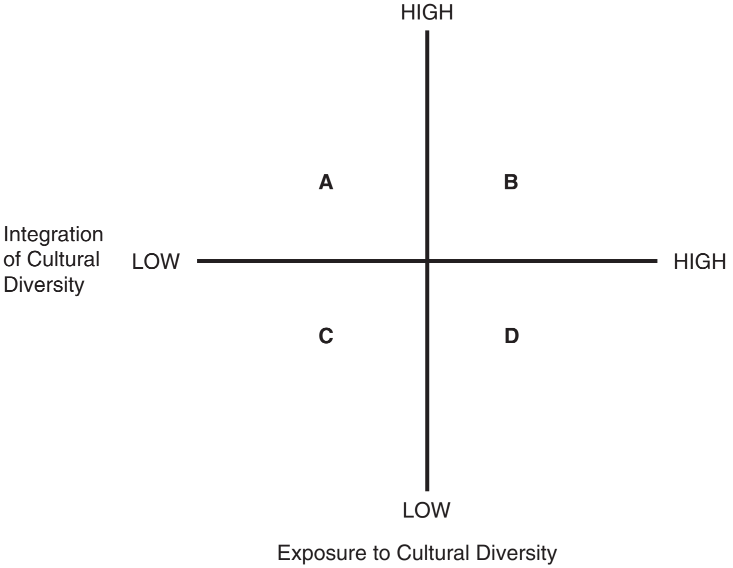

Figure 8.2 *Variations in the exposure to and integration of cultural diversity.*

Even when a single mind experiences the same set of external stimuli again, they are never experienced in the same way. Every experience is not only very personal but even for the same individual each experience is unique. As Michael Polanyi (1962) taught us many years ago, no two individuals see things in the same way.

The mind is biographical, but each step in the biography is highly unique and dependent on the previous step. Paraphrasing Stephen J. Gould (1989: 14), Dempsey writes: 'Wind the tape of the mind to its early days, [. . .] let it play again from an identical starting point, and the chance becomes vanishingly small that anything like the identical mind will grace the replay' (1996).

In Figure 8.2, two or more individuals may grow up in environments with exposure to high levels of cultural diversity (Cells A and B). However, even when children in the same family grow up in multicultural environments, perhaps only one child (Cell A) may internalize a high degree of cultural diversity and hence the potential to develop a high degree of cognitive complexity. As suggested above, children growing up in similar environments experience it differently. In short, growing up in a multicultural environment increases the likelihood of internalizing cultural diversity and of developing high cognitive complexity, but there is no certainty that this will occur. The cognitive development of individuals involves a high degree of chance and contingency (Edelman and Gally, 2001; Greenspan, 2001a; 2001b).

At one level, this poses a great difficulty for scientific work at the laboratory level. Replication is at the heart of the scientific enterprise. But at a very deep level, each scientist tends to see the same experiment in a very different way – even when repeated over and over – though very often the differences are extremely small. If two scientists, each with a mind having high levels of cognitive complexity and scientific diversity, can work together, there is much greater potential that because of their intense interaction, they may understand complex phenomena in novel ways. Because each mind experiences stimuli in very different ways, one of the great challenges to a scientist is to translate personal knowledge to codified knowledge, to communicate what is observed in one mind to a larger community (Judson, 2004: 39–40; Polanyi, 1962; 1966).

Individuals who have high cognitive complexity tend to have the capacity to understand the phenomena they study in multiple ways. They are rarely of 'one mind' about a problem. Because of their capacity to understand things in multiple ways, they often engage in paradoxical thinking (Dempsey, 1996; Minsky, 1995). And it is the result of this capacity to see things in very complex and novel ways that the scientific community occasionally labels as a major discovery (Hollingsworth *et al.*, 2008).

When I confront the question of whether my findings and hypotheses about high cognitive complexity and major discoveries are consistent with recent trends in neuroscience, it is necessary to place some constraints on the answer to such a problem. The scientific field broadly labelled neuroscience as extremely heterogeneous, consisting of dozens if not several hundred sub-specialities. However, my findings and hypotheses about the complexity of experiences, high cognitive complexity and major discoveries are consistent with the work of a number of theoretically oriented neuroscientists who are very macro-oriented and who attempt to understand the interconnections among multiple parts of the brain (Dalton, 2002: chapters 9 and 10; Dempsey, 1996; Edelman, 1987; 1989; 1992; Hayek, 1952; Rizzello, 1997; 2003).

Concluding Observations

The research reported herein is a small part of a large-scale, multi-level research project which attempts to understand why societies, organizations and within organizations, departments and laboratories vary in having major breakthroughs in basic biomedical science. This project is based on many years of research about these multiple levels throughout the twentieth century in the countries of Britain, France, Germany and the US. This essay has focused only at one of these levels – essentially the laboratory – and even there the focus has not been on the structure of the laboratory but on some of the personal characteristics of those associated most intimately with the making of major discoveries in basic biomedical science. Table 8.4 is somewhat broader in that it also includes a few scientists in physics and mathematics who also attained high distinction in science.

The reader should recognize that whenever one is writing historically about the psychology or social psychology of individuals or collections of individuals, the data are much less ideal than the data to which the psychologist has access in the laboratory or the clinic. In this essay, the data is retrospective in nature and is obtained from many sources. While the author has interviewed more than 450 individuals in connection with the larger multi-level, cross-temporal and cross-national research project, he has interviewed less than 25 per cent of the individuals on whom data is reported herein. As suggested previously, most of the data was obtained from the various types of sources discussed above.

This essay is heuristic in nature, written in the spirit of suggesting an agenda for further research about the kinds of individuals associated with the making of major discoveries. Hopefully, others will follow up with similar studies involving other fields of science and will subject the views presented herein to critical analysis. It is through the interactive process of proposing new ideas and subjecting them to rigorous testing that we may make fundamental advances in science. This essay is essentially at the stage of hypothesis and/or theory generation. As McDonagh (2000: 678) emphasizes, good dialogue in science requires that generalizations be replicated by researchers independent of the proponent of new ideas before the scientific community at large accepts the arguments as valid.

The essay has implications for those interested in the most effective way of organizing science in order to maximize the potential for major discoveries. Our research has identified the sociological properties associated with laboratories where major discoveries have occurred in basic biomedical science. But as this essay emphasizes, major discoveries are rare events. A scientist may design a laboratory with all the characteristics of a Type A lab and yet no major discovery may occur. The kind of mind of the scientist who makes a major discovery is a major factor in the explanation of the discovery process, and our knowledge of this subject has hitherto been underdeveloped. This essay attempts to contribute to the understanding of the kinds of minds associated with major discoveries.

At one level, the insights which this essay sheds on the process of discovery are somewhat discouraging. I have found that the minds of great discoverers tend to evolve in an unplanned, chaotic, somewhat random process involving a considerable amount of chance, luck and contingency. Cognitive complexity cannot be imparted in the classroom or curriculum by pedagogical technique. No matter how much we invest in training the young scientist to be excellent, this essay suggests that in the final analysis, it is idiosyncratic characteristics operating at the individual level which are decisive in determining who will make the major discovery. On the other hand, the individual who internalizes all the factors consistent with high degrees of innovativeness is unlikely to be very innovative without the opportunity to be in the structural and cultural environments where the scientist's potential can be realized (Hollingsworth and Hollingsworth, 2000). In the final analysis, those responsible for recruiting scientists would be well advised to give high consideration to individuals with high cognitive complexity.

Endnotes

1 Earlier versions of this essay were presented as lectures at the Neurosciences Institute in La Jolla, California; at the conference on Dewey, Hayek and Embodied Cognition: Experience, Beliefs and Rules, at the American Institute for Economic Research in Great Barrington Massachusetts; at the Society for Advancement of Socio-Economics Annual Meeting in Aix-en-Provence, France; and at the Atlanta Conference on Science and Technology Policy 2006: US-EU Policies for Research and Innovation. But it was Margie Mendell and her colleagues in Montreal in the Research Center on Social Innovations who provided the opportunity to write this essay while I was a visiting professor at the University of Québec in the fall of 2004.

2 My collaborators in the original study of discoveries and their organizational contexts were Jerald Hage and Ellen Jane Hollingsworth. Without their assistance this essay would not have been possible. David Gear's assistance in the larger project as well as in the research for and writing of this essay has been virtually indispensable. Ellen Jane Hollingsworth and David Gear kindly read multiple drafts of the essay and did much to improve it. Marcel Fourier and Arnaud Sales also made useful comments on an earlier draft. Katharine Rosenberry discussed the subject of creativity with me at length, and those discussions were very helpful in clarifying my thoughts on the subject. Much of the inspiration for this essay came from the work of Robert Root-Bernstein. His previous work about the achievements of scientists in various domains has been especially helpful. Over the years, my colleagues at the Neurosciences Institute in La Jolla, California, particularly Dr. Gerald Edelman, have taught me a great deal about neuroscience.

3 Some years ago, my colleague Jerald Hage first introduced me to the concept cognitive complexity, though subsequently he has used the concept somewhat differently from the way it is operationalized in this essay (see Hage and Powers, 1992; on cognitive complexity, also see Ceci and Liker, 1986; Conway *et al*., 2001; Schaller, 1994).

4 In recent years we have had a number of excellent studies of single laboratories in basic biomedical science: Holmes, 1993; 2001; Kleinman, 2003; Latour, 1987; Rheinberger, 1997. But very few of these studies have been comparative in nature, and the authors have not developed theoretical generalizations about the types of individuals associated with particular types of laboratories. Thus, our research on laboratories departs from much of the existing literature.

5 More than 90 per cent of the individuals in this table had two Jewish parents. Also listed are a few individuals who had one parent who was Jewish and one who was not. Several (e.g. Karl Landsteiner and Gerty Cori) converted from Judaism to Catholicism. For purposes of this essay, this kind of issue is not highly relevant, for the concern is whether the individual internalized multiple cultures. Anyone who reads the biographies of Landsteiner (Rous, 1945; Speiser and Smekal, 1975) or Cori (McGrayne, 1993) will observe that they clearly internalized multiple cultures – partly because of their Jewish ancestry. For additional information on this subject, see Hargittai (2002).

6 For a thorough treatment of biological scientists under the Nazis, see Deichmann (1996).

7 Obviously, there were very innovative Polish Jews. An interesting case was the career of the Polish-born Nobel laureate Andrew Schally who was Jewish but whose father was a professional soldier who later became a major general in the Allied forces during the Second World War. The example of Schally is clear evidence that even in a culture where there is extreme discrimination, under certain circumstances it is possible for an individual to internalize the society's multiple cultures (Acker, 1991; Wade, 1981).

8 In the preparation of the material for Table 8.4, I am not only indebted to all of the individuals whom I interviewed for this essay (see references below) but especially to the scholarship of Robert Scott Root-Bernstein and to the following published references: Brandmüller and Claus, 1982; Curtin, 1982; Eiduson, 1962; Furguson, 1977; Hammond, 1985; Hindle, 1981; Kassler, 1982; Lepage, 1961; Levarie, 1980; Miller, 1984; Nachmansohn, 1979, Nickles, 1980; Nye, 2004; Ostwald, 1912; Rauscher and Shaw, 1998; Ritterbush, 1968; Roe, 1951, 1953; Root-Bernstein, 1989; Root-Bernstein and Root-Bernstein, 1999; Sime, 1996; Van't Hoff, 1967; Waddington, 1969; Wechsler, 1978.

9 Weisskopf uses the concept complementarity in the sense that Neils Bohr occasionally spoke about the subject. For further discussion on this issue, see Hollingsworth and Gear (2004).

10 There has been considerable controversy about the effect of birth order on the behaviour of children. Even so, there is considerable literature which demonstrates that birth order within families influences the behaviour of children. See Politics and the Life Sciences (2000) for an extensive discussion of the literature on the subject. Also, see Dalton (2004).

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