IN THIS CHAPTER, WE FOCUS ON THE PERSONAL CHARACTERISTICS OF CREATIVE SCIENTISTS. WE SHALL FIRST TRY TO IDENTIFY THOSE CHARACTERISTICS WHICH HAVE SHOWN SOME CONSISTENCY IN DIFFERENTIATING CREATIVE FROM LESS CREATIVE SCIENTISTS. LATER, WE SHALL SPECULATE ABOUT THE ROLE OF PERSONAL CHARACTERISTICS IN THE DEVELOPMENT OF AUCTORIVE SCIENTIFIC CREATIVITY.

BEFORE IDENTIFYING THE PERSONAL CHARACTERISTICS, HOWEVER, WE WOULD LIKE TO COMMENT ON THE WAYS IN WHICH OUR APPROACH DIFFERS FROM THAT OF THE MANY OTHER PSYCHOLOGISTS (E.G., CHAMBERS, 1969; DELIAS AND GAIER, 1970; TORRANCE, 1962) WHO HAVE WRITTEN ABOUT PERSONAL CHARACTERISTICS ASSOCIATED WITH CREATIVITY. FIRST, OTHER WRITERS HAVE INCLUDED MANY CHARACTERISTICS WHICH HAVE RECEIVED LITTLE OR NO SUPPORT IN STUDIES OF AUCTORS. DIVERGENT THINKING ABILITIES, CONSIDERED BY MANY WRITERS (E.G., CHAMBERS, 1969; GUILFORD, 1967A) TO BE IMPORTANT TO CREATIVITY, ARE A CASE IN POINT. ACCORDINGLY, WE SHALL
focus on the few auctorive characteristics which have received empirical support in studies using real-life creativity criteria.

Second, some writers have not always relied on evidence from persons showing real-life creative performance. Some writers have searched for personal characteristics associated with creativity test performance. But since no creativity test has consistently shown high correlations with measures of real-life creativity, we believe that the only way to understand real-life creativity is to study it directly.

A third way in which our approach differs from that of other psychologists is that we limit our focus to science and related fields. Other psychologists have often assumed that personal characteristics of creative persons hold across fields as diverse as art, writing, and science. Although this position may be correct, there is little evidence for it. Almost all the studies relating real-life creativity to personal characteristics have been conducted with persons in scientific and related fields. Accordingly, we shall not attempt to generalize beyond scientifically oriented fields.

We believe there is a continuum of creativity among auctors. Publishing original research is not the same as doing Nobel prize-winning work. We tentatively assume, however, that the personal characteristics associated with creativity at the lower end of the auctorive continuum are also associated with creativity at the higher end of the continuum.

In the studies of auctors, a special problem is posed by the abundance of inconsistent results. To be sure, several characteristics have shown fair consistency in differentiating auctors from less creative persons. Still, it is common to find a characteristic differentiating auctors in one study but not in others. Inconsistent results are to be expected when studies sample subjects from different fields, use different criteria for identifying cre-

ative and less creative subgroups, and employ research designs differing in the sophistication of methodological controls. We list only those characteristics which have shown consistency across fields. The evidence supporting these characteristics is briefly discussed.

**Characteristics Necessary for a Scientific Career**

The first three characteristics to be considered should be viewed as preconditions for the attainment of a professional level of expertise in a field. These preconditions differentiate auctors from the general public, although not from less creative professionals in the same field.

**Above Average Intelligence**

Most researchers studying auctors have reported that auctors possess substantially above average intelligence (e.g., Barron, 1969; Helson, 1971; MacKinnon, 1962a; Roe, 1965). A high IQ is probably necessary for admission to and completion of an advanced graduate program. However, as is apparent from the criterion-related validity studies of intelligence tests, which are reviewed in Appendix A, a high IQ does not usually differentiate creative from less creative professionals in the same field. A threshold effect seems to operate for IQ (MacKinnon, 1968b; Meer and Stein, 1955), such that, above a certain level required for mastery of a field, IQ is not correlated with creativity. The IQ threshold probably varies from one field to another; it is probably higher in scientific than in artistic fields.

More specific mental abilities, which are required for auctorive creativity in particular fields, probably show similar threshold effects. Examples of such abilities include numerical ability in mathematics, spatial ability in architecture, and verbal ability in prose or poetry. Other mental abilities may be important in music and art.
Extensive Training in a Field

This characteristic is a self-evident condition for creative accomplishment in most areas of human endeavor (e.g., Ypma, 1968). Most fields are sufficiently differentiated that aspiring actors must master the existing knowledge and theory in an area before they have a chance of making a creative contribution. This mastery is normally attained in graduate degree programs, which demand for their completion a high degree of persistence.

Emotional Adjustment

A minimal level of emotional adjustment is another self-evident requirement for creative creativity. The level of adjustment must be high enough to allow sustained work to be done (Roe, 1951b). Thus a low threshold probably operates for this characteristic. Although there is abundant anecdotal evidence about actors' adjustment or lack thereof, little systematic research has been conducted on this topic. One relevant finding is Chambers' (1964) report that both creative and comparison groups of chemists and psychologists fell in the average range in their feelings of security versus insecurity.

Characteristics of Creative Scientists

Let us turn from characteristics that are prerequisite for a professional career and consider the personal characteristics distinguishing actors from less creative persons in the same field.

Autonomy

The independence of actors is stressed by virtually everyone who has theorized about highly creative adult professionals (e.g., Chambers, 1969; Dellas and Gaier, 1970). This independence and rejection of outside influences has been documented for architects (MacKinnon, 1962a, 1962b, 1964), petroleum research scientists (Morgan, 1961), research chemists (Stein, 1962, 1963; Ypma, 1968), physical and biological scientists (Roe, 1951a, 1951b, 1952, 1953), industrial research scientists (Ypma, 1968), and female mathematicians (Helson, 1971). For example, MacKinnon (1962a), describing his creative architects, viewed independence as a central trait, already well-established when the architects were in college:

They were unwilling to accept anything on the mere say-so of their instructors. Nothing was to be accepted on faith or because it had behind it the voice of authority. Such matters might be accepted, but only after the student on his own had demonstrated their validity to himself. (P. 494)

Evidence for the independence of actors also comes from studies, reviewed in chapter 2, showing these persons consistently score higher than less creative professionals on the autonomy scale of the Adjective Check List.

Personal Flexibility and Openness to Experience

These and similar characteristics have been emphasized by Chambers (1969) and MacKinnon (1962a). The importance of flexibility is supported by research with the flexibility scale of the California Psychological Inventory, which has differentiated actors from less creative persons in a variety of fields (see chapter 2). The items on this scale appear to tap tolerance for uncertainty and complexity; high scorers are unconcerned with order or strict adherence to rules and routines. Additional evidence for the importance of flexibility is provided by Ypma's (1968) finding that industrial research scientists who were more creative preferred a job in which they were "free to experiment with and try new methods."

The importance of openness to experience is supported by studies using the lability scale of the Adjective Check
List (see chapter 2). The lability scale, which has differentiated actors from less creative adult professionals, appears to identify persons who are open to their emotions and are adventurous and imaginative.

**Need to Be Original and Novel**

Many researchers (Arieti, 1976; Bergum, 1975; Chambers, 1964; MacKinnon, 1963; Ypma, 1968) have observed that highly creative persons view themselves as creative and consciously strive to be original. Consider, for example, MacKinnon's (1963) description of the creative architects he studied:

Above all else he [the creative architect] thinks of himself as imaginative; unquestionably committed to creative endeavor; unceasingly striving for creative solutions to the difficult problems he repeatedly sets for himself; satisfied only with solutions which are original and meet his own high standards of architectural excellence. . . .

(P. 276)

The more creative scientists studied by Chambers (1964) also expressed a need to be imaginative and original. Chambers found that:

When seeking a position, the less creative scientists are predominantly concerned with opportunities to combine teaching and administrative duties with research, while the overwhelming choice for the creative scientists is the opportunity to do really creative research and to choose problems of interest to them. (P. 6)

Additional evidence is provided by Ypma (1968), who found that responses to the question, How creative do you feel you are?, validly predicted creativity for three samples of industrial research scientists. When asked about the major motivating force in their lives, the more creative scientists were likely to answer: To come up with something new. First-person accounts of scientists (e.g., Austin, 1978) also give support to the existence of a strong need for originality and novelty in creative scientists.

**Need for Professional Recognition**

This need for recognition by one's peers is often denied by creative persons, yet there is ample evidence for its importance (e.g., Roe, 1965; Merton, 1973). For example, a large number of disputes among scientists have stemmed from priority claims (Merton, 1973, chapters 14 and 18). The existence of honorary societies, honorary degrees, and distinguished achievement awards also testifies to this need.

Creative persons tend to score lower on the deference scale of the Adjective Check List and higher in assertiveness (vs. humbleness) on the Sixteen Personality Factor Questionnaire (see chapter 2). In addition, MacKinnon (1964) reported that an IPAR self-assertive-

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1. More recently, Maddi (1975) has changed his position on novelty as a motivator for creative endeavor and has suggested instead that creativity may be better explained by the need to avoid alienation.
Commitment to Work

Studies of actuors consistently show that they work harder and longer and are more productive than their less creative peers (Chambers, 1964; Roe, 1951a, 1951b, 1965; Ypma, 1968). Accounts by creative scientists (e.g., Loewi, 1953) also emphasize this commitment to work. Chambers found that the creative chemists and psychologists he studied read more professional journals, presented more papers at conventions, and produced many more articles than did control groups of chemists and psychologists; this evidence of greater productive energy was also evident while the subjects were still in graduate school.

Often, this work commitment involves the subordination of nearly everything else (Helson, 1971; Roe, 1951b; Ypma, 1968). Roe, for example, described a group of eminent physical scientists as follows:

There is only one thing which seems to characterize the total group, and that is absorption in their work, over long years, and frequently to the exclusion of everything else. This was also true of the biologists. This one thing alone is probably not of itself sufficient to account for the success enjoyed by these men, but it appears to be a sine qua non. It needs to be accompanied by a certain amount of intelligence, and by sufficient emotional and social adjustment that it is possible to maintain a position in which the work can be done. (Pp. 233–34)

The high level of task commitment is coupled with self-directed motivation (Chambers, 1964; MacKinnon, 1961; Ypma, 1968). MacKinnon (1961) observed that his creative architects were strongly motivated to achieve in situations requiring independent thought and action, rather than conformity. Similarly, Chambers (1964), studying creative chemists and psychologists, concluded that the creative scientist

is not the type of person who waits for someone else to tell him what to do, but rather thinks things through and then takes action on his own with little regard to convention or current "fashion." (P. 14)

The three motivational characteristics we have identified—need to be original and novel, need for professional recognition, and commitment to work—have far-reaching implications for the personal lives of actuors. For example, aspiring actuors, at least at the start of their careers, may find that their need to be original necessitates financial sacrifices. But potentially more serious are the consequences of commitment to work. If the commitment is extreme, family and personal relationships are sure to suffer, and there will be little time for hobbies or activities leading to personal growth. These problems, of course, are not limited to actuors but are the price paid by anyone for whom work is the highest priority.

Aesthetic Sensitivity

Although this characteristic is not well established, there is some evidence that actuors show greater aesthetic sensitivity than their less creative peers. Actuors tend to score high on the Barron-Welsh Art Scale, which taps preference for complex and asymmetrical line drawings; on the Mosaic Construction Test, actuors tend to achieve high ratings of overall artistic merit (see chapter 2). Further evidence for the importance of aesthetic sensitivity is provided by Clifford's (1958) finding that twelve of seventeen highly creative chemists and mathematicians experienced aesthetic satisfaction from their work. In a similar vein, MacKinnon (1962a) noted that a creative person demands that "solutions be elegant. He seeks both truth and beauty" (p. 490). Also, Zuckerman (1977, p. 128) reported that many Nobel laureates
she interviewed "identified 'simplicity' of solutions as a mark of scientific taste." And psychologist L. L. Thurstone (1964, p. 15) expressed the view that "creative scientific work is largely artistic in character." The role of beauty and simplicity in creative scientific work has also been emphasized by Chandrasekhar (1975), an astronomer, Rollo May (1975), a psychoanalyst, and S. M. Ulam (1976), a mathematician.

Summary of Personal Characteristics

A number of characteristics seem applicable to auctors across fields. Above average IQ, extensive training in a field, and at least a minimal level of emotional adjustment function as preconditions necessary for the attainment of a professional level of expertise. Among persons who reach this level, several other characteristics are associated with auctorive creativity and probably contribute to its development. These include the need to be original and novel, the need for professional recognition, commitment to work, personal flexibility, openness to experience, and autonomy. Aesthetic sensitivity may be an additional characteristic, although the evidence for its importance is less well established.

A MODEL OF AUCTORIVE CREATIVITY

Virtually all scientists seem to have certain characteristics necessary for a scientific career: high intelligence, extensive training, and at least moderate socio-emotional adjustment. But the more creative scientists are also likely to show high levels on the six other characteristics we enumerated: autonomy, personal flexibility, need to be original and novel, need for professional recognition, commitment to work, and aesthetic sensitivity. On the basis of these findings, we offer a model which, though frankly speculative, can explain a number of phenomena associated with auctorive creativity. We believe that the six personal characteristics of the more creative scientists all operate as causal influences, each increasing the likelihood that a scientist will produce creative work. We concede that the six characteristics, since they do appear with adult scientists, could logically be viewed as outcomes rather than causes of scientific creativity. To some extent, the relationships are probably bi-directional; but the evidence clearly suggests that these personal characteristics are more causes than effects. For example, there is evidence (Chambers, 1964; MacKinnon, 1962a; Ypma, 1968) that the characteristics of auctors were already well established when the auctors were in graduate school, long before they received professional recognition.

If a person is to become a creative scientist, he must first show the prerequisites of high intelligence, extensive training, and moderate socio-emotional adjustment. In addition, he must be generally high on the personal characteristics: low levels on one or two personal characteristics might occur, but they could be compensated for by unusually high levels on other personal characteristics. There is also the likelihood that the combination of disposing characteristics is multiplicative rather than additive (Meehl, 1965); and curvilinear relationships are possible, as well. The personal characteristics thus operate as predictor variables in a multiple regression equation which has creativity as the criterion variable.

Our model suggests reasons why the personal characteristics, when considered separately, show relatively small correlations with scientific creativity. If creativity depends on the joint occurrence of high levels on several characteristics, many scientists showing high levels on one of the characteristics will nevertheless show little evidence of creativity, because other important characteristics may be absent or present only at low levels. Allison and Stewart (1974, p. 597) have hypothesized that, as tasks become less routine, more characteristics of the individual become relevant to performance, with the result that the distribution of task performance be-
comes increasingly skewed. Although many persons have one or several of the relevant characteristics, only a few persons have all the characteristics necessary for task performance. Since creative science is anything but routine, it should require a number of different individual characteristics, most of which can be expected to show only small correlations with scientific creativity.

This view of auctortive creativity contradicts the conception of creativity as a normally distributed trait (e.g., Blade, 1963). This conception is not merely a straw man. As Ausubel (1968) and Nicholls (1972) pointed out, much creativity research with children and adolescents has implicitly or explicitly assumed creativity is a normally distributed trait.

The personal characteristics should be viewed as relatively stable adult traits. They are neither immutable nor easily changed. They evolve gradually and become crystallized into fairly permanent traits once the scientists have become entrenched in their careers. Rewards, punishments, models, and situational factors (e.g., university or industrial work settings) probably influence the personal characteristics to some degree.

How do the personal characteristics lead to creative scientific accomplishments? To some extent, this question has already been answered. The personal characteristics influence the scientist's choice of job and choice of research problems. It seems self-evident that these choices then affect the chances of creative accomplishments. More directly, the personal characteristics influence the quantity and quality of work.

One advantage of the model is that it can explain the rareness of auctortive creativity. Many talented persons do not become auctors because they are very low on one or several of the personal characteristics. As a result, there are relatively few scientists who manifest high creativity but many who manifest little or none. A skewed distribution of creativity is consistent with the log normal distribution of number of publications by scientific personnel found by Shockley (1957).

Our model suggests the existence of different types of auctors. Detailed speculation would be premature, but types might be identified on the basis of unusually high levels on one or a few of the personal characteristics. For example, one type of auctor with an exceptionally high commitment to work might achieve creativity primarily through methodical plodding and dogged perseverance. Another type, high on flexibility and openness to experience, might achieve innovative insights by viewing a problem in terms of an analogy drawn from some field outside the field of the problem. Many different types of auctors can be derived from the proposed model, with ample room for individual eccentricity.

One important limitation of the model deserves mention: creativity is predicted only from a set of personal characteristics. But since auctortive creativity must occur at a particular time and in a particular social milieu, situational and societal factors may also facilitate or impede its expression. In Robert Merton's view (1973, p. 366), all discoveries would eventually be made independently by several persons because the appropriate environmental determinants are present. But Merton believes that "scientists of genius" can speed up this process because they can do the work of many average scientists.

As psychologists, we believe situational and societal factors may influence the personal characteristics that facilitate creativity. Merton, as a sociologist, takes the view that personal characteristics may facilitate or impede the workings of situational and societal forces.

**The Role of Chance in Scientific Creativity**

A model predicting scientific creativity on the basis of personal characteristics of scientists may appear overly deterministic, and some critics will argue we have neglected the role of chance in creativity. It cannot be denied that factors of chance often influence creative discoveries. For this reason, any model based on a set
of personal characteristics will always predict creativity imperfectly. However, chance often does not operate in isolation to affect creativity; in many cases, it works in conjunction with scientists' personal characteristics.

This point is perhaps best supported in Austin's book (1978) on the role of chance in scientific creativity. Austin identifies four types of chance. Chance I, or blind luck, does not depend on any personal characteristics of the recipient. But three other types of chance are directly linked to personal characteristics. In Chance II, good luck results from general exploratory behavior. That is, a scientist's energetic scientific activity increases the likelihood that random ideas in fresh combinations will lead to creative discoveries. According to Austin, Chance II depends on "curiosity about many things, persistence, willingness to experiment and to explore" (p. 78). These characteristics are closely related to ones we have discussed in our own model. Curiosity about many things seems related to the need to be original and novel; persistence is related to commitment to work; willingness to experiment and to explore is related to personal flexibility and openness to experience.

Austin's Chance III exemplifies Louis Pasteur's statement that chance favors the prepared mind. In Chance III, chance occurs in the form of a faint clue which is overlooked by everyone except a scientist who, because of training and experience, is uniquely prepared to observe it and to grasp its significance. Austin believes Chance III depends on the scientist's background of knowledge and on abilities to observe, remember, and quickly form significant new associations. In terms of our own model, above average intelligence, extensive training in a field, commitment to work, and personal flexibility all seem related to Chance III.

Austin's Chance IV expresses the principle that chance favors the individualized action. Fortuitous events occur when the scientist acts in a highly personalized way. Distinctive hobbies, personal lifestyles, and activities peculiar to the scientist as an individual may lead to a discovery. In terms of our own model, autonomy and generalized personal flexibility would increase the likelihood a scientist would have an unusual hobby or a distinctive lifestyle which could act as a catalyst for Chance IV.

In many cases, then, chance operates in conjunction with the personal characteristics we have found in creative scientists. We will return to the role of chance in chapter 5.

The Cultivation of Scientific Creativity

Our model suggests no simple guidelines for fostering scientific creativity. One must begin by selecting highly intelligent persons and educating them in science. Those who would enhance creativity might also consider influencing the development of relevant personal characteristics.

Each of these personal characteristics can probably be influenced by a variety of experiences at different times of life. Flexibility, for example, is probably influenced by parent-child interaction beginning in early childhood, by the breadth of experiences encountered over a lifetime, and by adult models encountered in and out of school, especially during adolescence. Since the profiles of creative scientists vary considerably on personal characteristics, many different antecedents of auctorial creativity must be possible. This diversity might explain why so few family and child-rearing variables have shown relationships to creativity. We shall review the evidence linking creativity to family and child-rearing variables in chapter 4.

Some experiences crucial to the development of scientific creativity may not occur until adulthood. One such experience may be an apprenticeship with a master in the field (Wallach, 1976). The apprenticeship seems especially important at the highest levels of scientific creativity. For example, Zuckerman (1965, 1977) re-
ported that more than half of American Nobel prize winners worked, as young scientists, under Nobel prize winners of earlier generations. Chambers (1973) also found that the development of creative scientists was strongly influenced by long-term, one-to-one experiences with professors in graduate school.

Can scientific creativity be attained through training? Training for creativity has been a perennial concern of some creativity researchers and many educators. Existing creativity training programs (e.g., Feldhusen, Treffinger, and Bahlke, 1970; Parnes, Noller, and Biondi, 1977) often attempt to influence divergent thinking abilities. But there is little evidence that these abilities are important to scientific creativity. Studies of these programs, therefore, can tell us little about the possibility of training for scientific creativity (e.g., Mansfield and Busse, 1974; Mansfield, Busse, and Krepelka, 1978). However, programs like the ones developed at Johns Hopkins University for gifted and talented youth are effective in helping youngsters master subjects such as mathematics at a greatly increased rate (Keating, 1976; Stanley, George, and Solano, 1977; Stanley, Keating, and Fox, 1974). The Johns Hopkins programs focus on the early identification and acceleration of very bright children identified largely through conventional tests, but they do not directly attempt to foster creativity.

Perhaps the most that training can accomplish is to facilitate the development of scientific creativity in persons already highly selected on the basis of predisposing factors. This is what ideally happens in superior graduate programs, although the selection process often over-emphasizes cognitive abilities and under-emphasizes non-cognitive, personal characteristics.

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**Child-Rearing Influences on Creativity in Science**

**Up to this point, we have focused on adult creativity; but because we believe that the childhood experiences of creative persons are of great interest to parents and teachers, we will try here to present the best evidence available on the subject. There have been few studies of the child-rearing experiences of creative adults; therefore, we have broadened our review to include studies using high school and college students. It seems preferable to reach conclusions with limited applicability than to reach no conclusions at all.**

We realize that, by considering both adults and students, we are implicitly assuming that real-life creativity has similar antecedents at the auctorive and at the amateur level. This assumption is tentative, but there is some evidence that auctors are likely to emerge from the ranks of young persons showing creativity at the

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Processes Used by Creative Scientists

Chapter 3 dealt with the characteristics of auctors. To understand why these personal characteristics are important, we must understand the processes used by auctors in their work. Many theories have been developed to explain the creative process. The diverse perspectives of the theories include psychoanalysis (Arieti, 1976; Kris, 1952; Kubie, 1958), Gestalt theory (Köhler, 1969; Wertheimer, 1959), associationism (Mednick, 1962), perception (Schachtel, 1959), humanism (Maslow, 1959, 1967; Rogers, 1959), and cognitive developmental theory (Feldman, 1974). Still other theories combine selected elements from a variety of perspectives (e.g., Gruber, 1974; Hadamard, 1945; Haslerud, 1972; Koestler, 1964). A review of these and other theories can be found elsewhere (Busse and Mansfield, 1980). Our theory differs from most of these in that we focus on creative processes only in scientific fields.

What kinds of studies can be used to gain insights about the processes used by creative scientists? In chapter 3, we argued that the personal characteristics of auctors can be best understood through studies of auctors.
The same argument applies to the processes used by authors. However, the lack of controlled studies of creative processes used by authors in scientific fields forces a reliance upon descriptive personal accounts, which are subject to bias and distortion. A scientist may, for example, unconsciously alter his report to make it conform to some view of the scientific method. In one significant case, however, the objection of retrospective bias does not apply. Charles Darwin kept voluminous notebooks in which he recorded his thinking. Because Darwin dated many of the entries in his notebooks, it is possible to follow the course of his thinking.

Since generalizations made from a single case are limited, we also rely on personal accounts by other scientists. Although these accounts are susceptible to distortion and omission, they do show similarities to each other and to the processes revealed in Darwin’s notebooks and therefore help to illuminate the processes of scientific creativity.

The scientists considered in this chapter are among the most creative in the history of science; in our terminology, they are at the upper end of the auctorive continuum. Many of the studies reviewed in earlier chapters investigated creativity among more average scientists. Certainly, there are differences between creative geniuses and creative Ph.D.’s in industry or in a university; but it seems reasonable to suppose that the processes they employ are similar.

We shall try to identify several essential processes occurring in the development of auctorive scientific products. These processes do not operate in isolation but rather interact and facilitate each other. Nor do they always occur in the sequence in which they are presented: the mind of the scientist does not usually proceed in an orderly, rational manner.

Examples of the processes will be drawn primarily from accounts of four scientists: James Watson (Olby, 1974; Watson, 1968), who, with two other researchers, was awarded the Nobel prize for discovery of the structure of DNA and the mechanism of genetic transmission; Albert Einstein (Wertheimer, 1959, pp. 213–33), who revolutionized physics with his theory of relativity; Johannes Kepler (Koestler, 1964, pp. 124–30), who showed that planetary orbits are elliptical; and Marie Curie (Curie, 1937), who, with her husband, Pierre, first identified radium and polonium. Following presentation of the processes, we shall illustrate their operation in one of the most detailed accounts available of a scientific discovery—Charles Darwin’s thinking that led to his theory of evolution.

**Selection of the Problem**

If a scientist is to make a creative breakthrough, he should select a problem that is ready to be solved; the solution must be at least remotely possible, given the instruments, methods, and knowledge available to him. Or, to paraphrase Otto Warburg, research is the art of finding problems that can be solved (Austin, 1978, p. 168). A number of investigators (e.g., Getzels and Csikszentmihalyi, 1975, 1976; Hadamard, 1945; Rokeach, 1965) have emphasized the importance of problem finding or problem selection.

Sometimes the possibility of a creative solution is obvious to an investigator from the outset. James Watson, for example, concentrated on discovering the structure of DNA, because he believed that solution of this problem would reveal the mechanism of genetic transmission. In other cases, a scientist may not be aware of the possibility of a creative outcome at the start of a line of inquiry, but his work is guided by a sensitivity to research findings that present problems for existing theory. Einstein, for example, in the thinking that eventually led to the theory of relativity, noticed that the Newtonian laws governing mechanical processes could not easily be applied to light. Newton had established that there could be no such thing as absolute motion or
absolute rest; it seemed clear that the same laws should apply to light. But Einstein noticed that the assumption of a variable velocity of light was incompatible with known electromagnetic phenomena.

Another well-known example of auctitive creativity arising from sensitivity to a problem is the case of Kepler's formulation of elliptical planetary orbits. Kepler was troubled by the fact that the accurate instruments and methods developed by Tycho de Brahe for recording positions of stars and planets had produced data showing that the observed positions of Mars differed by as much as eight minutes of arc from those predicted by the then accepted Ptolemaic theory, which explained the motion of planets by principles based on circular motion. Eventually, Kepler saw that the observed movement of Mars could be explained only by discarding the Ptolemaic belief of motion in perfect circles. When Kepler substituted the notion of oval planetary orbits around the sun, he had to explain the oval shape of the orbits. Since this could be done only by assuming that the orbits resulted from two antagonistic forces, Kepler was led to create a new theory, one which applied the laws of physics to celestial bodies.

In the development of auctitive products, the importance of sensitivity to problems cannot be overemphasized. B. F. Skinner (1959), discussing one of his findings, argues that such sensitivity should guide all scientific research:

The major result of this experiment was that some of my rats had babies. I began to watch young rats. I saw them right themselves and crawl about very much like the decerebrate or thalamic cats and rabbits of Magnus. So I set about studying the postural reflexes of young rats. Here was a first principle not formally recognized by scientific methodologists: when you run onto something interesting, drop everything else and study it. (P. 363)

Such serendipitous events leading to the selection of important problems are apparently quite common (e.g., Austin, 1978; Barber and Fox, 1962; Cannon, 1945, pp. 68–78; Merton, 1968, pp. 157–62; Rosner and Abt, 1972, pp. 7–25).

It is likely that sensitivity in the selection of research problems is a primary factor differentiating auctitive scientists from less creative ones.

EXTENDED EFFORT TO SOLVE A PROBLEM

Creative accomplishments in science do not come easily. In the case of a major discovery, there is almost always an extended period of persistent effort before a solution begins to emerge. Francis Crick and James Watson, for example, spent a year and a half trying to discover the structure of DNA before developing the model that won them a Nobel prize. Einstein spent seven years working on the problem of the velocity of light in relation to different frames of reference before he hit upon the key to the solution and developed his theory of special relativity. Many other examples of persistent effort could be mentioned. The amount of effort and time required in this phase of the creative process varies within wide limits, but it is probably great enough to deter all but the most highly motivated scientists.

One reason for the importance of a period of extended effort is that it increases the likelihood that chance associations will provide clues to the solution of the problem. Austin (1978) observes that chance sometimes operates as a result of a scientist's general exploratory behavior. The scientist who is persistent in investigating a problem is more likely to be the beneficiary of chance. Austin also proposes that chance favors the prepared mind. The importance of the period of extended effort may be to heighten the scientist's receptivity to ideas or associations that are not obviously related to the problem but provide important clues to its solution.
Setting Constraints on the Solution of the Problem

In the period of extended effort to solve the problem, the scientist adopts a number of constraints on the problem's solution. A constraint can be broadly conceived as any mental set which limits the scope within which the inquiry is conducted. Constraints can be classified as empirical, theoretical, and methodological. Some constraints are present initially; others are added as new insights develop.

Empirical Constraints

The most obvious type of constraint is imposed by experimental observations or results. Marie Curie, in her study of radioactivity, found that samples of pitchblende produced far more radiation than could be explained by the quantities of uranium and thorium present. Since uranium and thorium were the only two known radioactive elements, this finding led to the search for new elements. For Einstein the most important empirical constraint in the work leading to the theory of relativity was the Michelson-Morely finding, which suggested that the speed of light was independent of any particular frame of reference. Finally, consider the influence on Kepler of Tycho de Brahe's observations showing that the orbit of Mars failed, by up to eight minutes of arc, to conform to predictions based on the Ptolemaic theory of circular planetary motion. Although this discrepancy was small, it could not be ignored, for Tycho de Brahe had developed highly precise methods for observing the heavens.

Empirical findings, especially when they differ from theoretical predictions, probably constitute the single most important type of constraint. Indeed, an essential aspect of the creative process is to recognize which empirical findings are especially important and to plan one's inquiry accordingly. In this sense, the setting of a constraint is closely related to the process of selecting a problem.

Theoretical Constraints

Constraints of this type are adopted with varying degrees of commitment. The theoretical constraints most tenaciously held are likely to be the central assumptions of a theory. Theoretical constraints of this type are similar to what Thomas Kuhn calls paradigms. Kuhn (1970, p. viii) defines paradigms as "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners." Because theoretical assumptions are often widely accepted, a scientist may be unaware that they are constraints. Einstein, for example, initially accepted the prevailing assumption that time was independent of physical processes and could be analyzed independent of any specific frame of reference. It was not until he questioned this constraint that he was able to develop his theory of relativity. Similarly, Kepler at first accepted the Ptolemaic assumption that planetary movement could be explained in terms of the simultaneous operation of circular components of motion. This constraint, like Einstein's initial assumption about time, proved wrong.

Other theoretical constraints, which we call "working hypotheses," are adopted more tentatively. Working hypotheses may be borrowed from other investigators, but often they are adopted by the investigator himself. For example, James Watson, who discovered the structure of DNA and the mechanism of genetic transmission, adopted the working hypothesis that DNA had a helical structure. Watson was influenced by Linus Pauling's demonstration of a helical structure in a protein molecule, as well as by his own demonstration of the helical structure of the tobacco mosaic virus. Eventually, improved X-ray diffraction data confirmed the working hypothesis and elevated it to the status of an empirical constraint.
Methodological Constraints

A third class of constraints, methodological ones, pertain to instrumentation, research strategy, and statistical analysis. The constraints imposed by instruments for obtaining data can be appreciated by considering the tremendous advances that have followed the development of new instruments such as the electron microscope in biology, the cyclotron in physics (Libby, 1970), and the radio telescope in astronomy (Edge and Mulkay, 1976).

The scientist’s strategy for obtaining data is another methodological constraint. Its importance is illustrated in James Watson’s (1968) account of his work on the structure of DNA. Watson adopted the technique of molecular model building because of the success Linus Pauling had achieved using this technique to discover the structure of another protein molecule:

The key to Linus’ success was his reliance on the simple laws of structural chemistry. The \( \alpha \)-(alpha)-helix had not been found by only staring at X-ray pictures; the essential trick, instead, was to ask which atoms like to sit next to each other. In place of pencil and paper, the main working tools were a set of molecular models superficially resembling the toys of preschool children. (Watson, 1968, p. 50)

Despite Pauling’s success, the technique of model building was not accepted by everyone. Another researcher, Rosalind Franklin, sought to decipher DNA through the analysis of X-ray diffraction patterns of crystallized samples of DNA.

Other methodological constraints are found in the statistical techniques for analyzing data. In the past thirty years, many new statistical techniques have been developed that allow highly complex analyses of data. In the social sciences, for example, techniques such as multiple regression, factor analysis, and multivariate analysis of variance have begun to revolutionize research.

Processes Used by Creative Scientists

The development of new statistical techniques has been facilitated by the computer. A relatively simple factor analysis that would take months to compute by hand can be accomplished in minutes by a computer.

Summary

We have identified three types of constraints: empirical, theoretical, and methodological. Some constraints, such as major empirical findings, central theoretical assumptions, and available instrumentation, cannot be ignored by the researcher. Other constraints, however, such as empirical findings in related fields, working hypotheses, and research strategies, must be discovered or selected. The choice of initial constraints is extremely important. It is almost inevitable that some initially adopted constraints will prove wrong; but errors in selection must be minimized. The working hypotheses must conform to all relevant empirical findings, and the methodology used must be capable of providing a solution.

Changing the Constraints

In the process of developing a scientific accomplishment, it is likely that some initially adopted constraints will prove wrong and will need to be changed. The process of changing constraints is similar to what Philip Jackson and Samuel Messick (1967) call transformation and what the Gestalt psychologists (e.g., Wertheimer, 1959) call restructuring.

Constraints in the form of working hypotheses are relatively easy to break, because they are deliberately adopted and are not part of a much larger system of beliefs. Working hypotheses may be discarded because newly discovered data make them untenable. For example, Watson found that his early model of DNA, which placed the sugar-phosphate backbone in the center of the helix rather than on the outside, was incompatible with the dual constraints imposed by the laws of structural chemistry and the X-ray diffraction patterns re-
revealed in photographs of DNA. When Watson was made aware of these problems, he shifted to a new working hypothesis and began to build models with an exterior backbone.

But constraints based on the central assumptions of a theory or paradigm (Kuhn, 1970) are much more difficult to change. Einstein worked for seven years on the problem of the velocity of light before breaking the constraint of traditional scientific theory regarding time. Breaking the constraints of a paradigm is probably impossible for many people. Thomas Kuhn (1970, p. 90) points out that paradigm change is most often achieved by men who are either very young or very new to a field and thus are not as strongly committed to existing paradigms.¹

The decision to break a constraint of a paradigm is often preceded by a long period of reluctance. Arthur Koestler (1964) cogently documents Kepler's reluctance to accept the idea of elliptical planetary orbits, although we need not accept his contention that the idea sprang from unconscious sources:

Kepler, too, nearly threw away the elliptic orbits; for almost three years he held the solution in his hands—without seeing it. His conscious mind refused to accept the "cartload of dung" which the underground had cast up. When the battle was over, he confessed: "Why should I mince my words? The truth of Nature, which I had rejected and chased away, returned by stealth through the backdoor, disguising itself to be accepted. Ah, what a foolish bird I have been!" (P. 217)

What makes a scientist decide to abandon the constraints of a paradigm? For one thing, there is generally significant experimental evidence which violates theoretical predictions and thus is not easily explained within the context of existing theory. In Einstein's case, this evidence was the Michelson-Morely experiment, while for Kepler it was the observed motion of Mars.

But the existence of such evidence is rarely sufficient to force the change of a paradigm. Almost any data can be made to appear consistent with a theory, provided that new assumptions are added to that theory. Consider the reaction of many physicists to the Michelson-Morely results, which were incompatible with the prediction of existing theory that the velocity of light would vary as a function of its direction with respect to the movement of the earth. Two of Einstein's contemporaries, Lorentz and Fitzgerald, postulated that the measurement apparatus contracted in the direction of the earth's motion. Although Einstein later demonstrated that this formulation was correct, he felt it had an ad hoc quality: no satisfactory explanation was provided for the hypothesized contraction. Nevertheless, the example illustrates the tendency of scientists to cling to an existing paradigm rather than to attempt to create a new one.

In addition to new data, an acceptable alternative theory may be necessary if the constraints of a paradigm are to be changed. Kuhn (1970, p. 77) makes the point that the scientific community never rejects a paradigm unless a plausible alternative is available.

But it is not easy to develop an alternative paradigm or theory. To do so requires viewing the problem from a perspective radically different from those generally used in the field. The accomplishment of this transformation or restructuring is not easy to explain. It seems to require two of the processes already discussed: extended effort, and sensitivity in selection of problems. The full complexity of the problem must be understood, and the most troublesome areas for existing theory must be pinpointed. Detecting troublesome areas is not always easy; it took Einstein a long time to realize that the Michelson-Morely experiment, which had seemed clear in every respect but its result, was really unclear in one

¹ Note that even relatively young scientists have completed a doctorate or the equivalent and thus have undergone extensive training.
crucial respect: the measurement of time. Systematic analysis of the meaning of simultaneity demonstrated to Einstein that the assumption that time could be measured independently of the observer's frame of reference was false. This was the crucial insight that led to a restructuring of traditional notions about space and movement and permitted Einstein to develop the theory of relativity.

Extended effort and sensitivity to problems may sometimes be sufficient by themselves to bring about restructuring. But another technique may also play a facilitating role: breaking away from the problem.

Many creative scientists have reported hitting upon a solution after having put the problem aside for a time. Sometimes the solution seemed to emerge suddenly and without any conscious precipitating association. The mathematician Poincaré (Ghiselin, 1952) describes such an experience:

Then I turned my attention to the study of some arithmetical questions apparently without much success and without a suspicion of any connection with my preceding researches. Disgusted with my failure, I went to spend a few days at the seaside and thought of something else. One morning, walking on the bluff, the idea came to me, with just the same characteristics of brevity, suddenness, and immediate certainty, that the arithmetic transformations of indeterminate ternary quadratic forms were identical with those of non-Euclidean geometry. (P. 26)

In other cases, the solution or restructuring is triggered by an association with some apparently unrelated thought. In either case, the solution or restructuring comes during a period when the scientist is not consciously trying to solve the problem. But why should putting aside a problem facilitate restructuring?

Arthur Koestler (1964), Henri Poincaré (Ghiselin, 1952), and Jacques Hadamard (1945) assume that unconscious processes are at work, but it is not necessary to attribute a unique creative role to unconscious processes. There is no question that unconscious processes can facilitate restructuring, as when, for example, an image from a dream suggests a new way of looking at a problem. But this does not mean that dreams or other unconscious processes hold the master key to creative thinking. We believe that Howard Gruber's (1974) view is more plausible:

The usual view of unconscious processes is that they express the way in which a person is divided against himself. But a person is not always so divided. When he bends all his efforts toward some great goal, the same problems which occupy his rational, waking thoughts will shape his imagery and pervade his dreams. (P. 246)

From our standpoint, breaking away from a problem allows a scientist to reapproach a problem with thoughts less dominated by the unproductive constraints which have hindered restructuring in the first place; it also allows him to think in an undirected fashion so that he is open to facilitating associations from random thoughts. In the latter case, a potentially useful idea will trigger analysis through directed thinking.

Chance often plays a key role in the changing of constraints. It may be through chance that the scientist is exposed to the idea or evidence which leads to a restructuring of the problem. As Austin (1978) points out, however, chance does not always operate independently of the scientist's behavior. The scientist who persistently attacks the problem from a variety of directions is likely to do something by chance that leads to the solution of the problem; and the scientist who has had extensive training and experience with a problem is highly sensitive to chance associations and facts that, though apparently unrelated to the problem, are in reality clues to its solution. In difficult problems, the critical associations may come from nonscientific areas, such as hobbies. In such cases, chance favors the scientist with a
distinctive life-style and highly personalized non-scientific activities.

**Verification and Elaboration**

The process of formulating new constraints and testing them is repeated until, by successive approximations, the scientist constructs a set of constraints leading to an acceptable solution. If the solution involves a major restructuring of the field or the introduction of a new paradigm, he must show that it provides a solution to the problems that plague the old paradigm, that it leads to an understanding of other problems not directly related to the scientist’s original concern, and that it suggests promising new lines of inquiry.

The time spent on these processes may be relatively short—as in the case of Einstein, who took only five weeks to develop his theory of special relativity after his initial insight into the meaning of time and simultaneity—or much longer—as in the case of Marie Curie, who worked for four years to isolate radium after she had first tentatively identified it as a new element. The processes of verification and elaboration are necessary for a new idea to gain acceptance by the scientific community.

**A Detailed Example of Creative Processes:**

**Darwin’s Development of the Theory of Evolution**

The processes of scientific creativity may be better understood by considering a single scientific accomplishment in some detail. For this purpose, we have reserved a highly detailed account: Darwin’s development of the theory of evolution through natural selection. We acknowledge our debt to Howard Gruber (1974) for his careful analysis of Darwin’s notebooks.

Darwin’s selection of the problem of evolution can be traced to his voyage on the *Beagle* to South America and the Galapagos Islands from 1831 to 1836, but his interest in evolution developed gradually and was the product of a number of different influences. During the voyage, Darwin recorded many thousands of notes. Among the phenomena he noticed was the tremendous variability of species; within an island group, slight variations of species could be observed from one island to the next. However, he was not struck by the evolutionary significance of these differences until after the end of his voyage, for, while at sea, he was primarily concerned with geological matters. Geology in Darwin’s time was riven by a conflict between those seeking to reconcile geological evidence with the biblical account of the creation and those seeking to explain the same evidence through a process of evolution governed by natural laws. Darwin followed this controversy and was gradually won over to the evolutionary viewpoint. But accepting this viewpoint created a conflict with his view that organisms lived in a stable, harmonious natural order:

As he came to accept modern geological views of a constantly changing order in the physical world, a contradiction within his point of view developed as follows: each species was adapted to its milieu; the milieu was undergoing constant change; and yet the species were changeless. (Gruber, 1974, p. 20)

**Darwin’s Selection of the Problem of Evolution**

Ten months after the *Beagle* docked in England, Darwin began his “transmutation” notebooks. From this point on, his goal was to develop a theory to explain evolution. At the same time, however, he believed that the concept of evolution would explain many phenomena relating to the geographic distribution of the species and the taxonomic relationships among them. Thus, Darwin’s evolving geological views, as well as his naturalistic observations during the voyage of the *Beagle*, sensitized him to problems which existing biological theory
could not adequately explain. Darwin’s desire to develop a theory of evolution became the “ruling passion” that guided a diverse set of research enterprises (Gruber, 1974, p. 251).

Constraints on Darwin’s Thinking

We turn now to a consideration of the constraints set by Darwin in his theory-building. Among the most important were those related to empirical observations. A theory of evolution would have to explain the tremendous variability of species and the existence of very similar species in neighboring geographical regions. Two additional empirical constraints were the geological evidence for an evolving world and the fossil evidence showing that many species had become extinct. These four empirical constraints implied evolution of the species and guided Darwin’s earliest attempts to develop a theory of evolution. Later on, he encountered other empirical evidence to which he also adapted his thinking.

Theoretical constraints were also important in guiding Darwin’s theory building. Certainly, Darwin’s thinking was not limited by the constraints of a scientific paradigm, since prior to Darwin’s time, no scientific paradigm governing either evolution or the variability of species existed. Although a few biologists had speculated about evolution, there was no satisfactory theory to explain it, and the biblical story of the creation remained prominent.

Nevertheless, Darwin’s thinking was constrained by a number of theoretical concepts or schemes, which we would classify as working hypotheses. Gruber (1974, pp. 117–28) identifies three schemes. The first is the image of the irregularly branching “Tree of Nature,” which Darwin used to explain the relationships among species, living and extinct. Another, the “conservation scheme,” appears in various guises in Darwin’s thought. In his first theory of evolution, later discarded, Darwin assumed that the number of extant species must remain approximately the same. This assumption, coupled with the evidence for extinction of species, led Darwin to believe that new species must constantly be emerging to take the place of those becoming extinct. A third theoretical constraint, identified by Gruber as the “equilibrium scheme,” refers to the principle that organisms adapt to environmental change.

Another more tentatively held working hypothesis was Darwin’s first evolutionary theory, the theory of monads, which was elaborated in his notebooks during July of 1837 (Gruber, 1974, pp. 136–37). This theory held that simple living particles, or monads, are constantly springing into life from inanimate matter as a result of unknown natural forces. In response to physical changes in the environment, the monads evolve, developing into ever more complex forms. Darwin believed that monads, like individual organisms, had a fixed life span and would eventually die. The monad theory was a constraint that Darwin maintained for only a few weeks.

Just as empirical and theoretical constraints guided Darwin’s thinking, so did methodological ones. Darwin’s research strategy is a prime example. For a long time, Darwin believed that he could not develop a satisfactory theory of evolution until he could explain the wide variability among species (Gruber, 1974, pp. 159–61). This research strategy was a methodological constraint which had to be modified before the development of a satisfactory theory was possible.

Darwin’s Changing of Constraints

Darwin’s thinking reflected changes in both theoretical and methodological constraints. Let us consider first the changing of a theoretical constraint—Darwin’s abandonment of the monad theory. The monad theory (Gruber, 1974, pp. 129–49) had been adopted to explain the existence of simple, one-celled organisms. It was believed that these organisms would have evolved into more com-
plex forms if they had been created long ago. Empirical evidence may have caused the monad theory to be discarded, for Darwin became aware of the work of Ehrenberg, which demonstrated the existence of fossilized unicellular animals identical to existing ones (Gruber, 1974, p. 153). Darwin realized that, if such simple animals had lived unchanged for tens of thousands of years, it was unnecessary to assume, as the monad theory did, that any simple organism must have arisen through recent spontaneous generation. Also, the assumption of a fixed life span for each monad led to the prediction that many species related to the same monad should die out simultaneously; but the available evidence clearly did not support this prediction.

Presumably, these problems caused Darwin to give up the monad theory; but the changing of this theoretical constraint may also have been facilitated by breaking away from the problem, for the monad theory disappeared from Darwin's notes following a four-week vacation.

The most famous example of constraint-changing in Darwin's thinking occurred at the time of his so-called "Malthusian insight." After about two years of searching for an explanation for evolution, Darwin read the Essay on Population, in which Thomas Malthus argued that population growth is geometrical, tempered only by factors such as disease and war, which lead to the elimination of maladaptive variants. Darwin's insight was that natural selection could also have a positive influence, favoring the occasional variants which were better adapted to the environmental conditions under which they must survive (Gruber, 1974, p. 105).

To arrive at this theory of evolution, Darwin had to modify several constraints. First, he had to recognize the Malthusian principle of superfecundity as a central theoretical constraint. Before this could be done, he had to abandon the monad theory, which assumed constant spontaneous generation of organisms, a superfecund al-ternative to the Malthusian superfecundity principle (Gruber, 1974, p. 105). The availability of new empirical data showing the dramatic rate of reproduction of microorganisms also helped to prepare Darwin to appreciate the importance of Malthusian superfecundity.

Darwin also had to modify a second constraint, a methodological one. In formulating a research strategy, he had assumed that a theory of evolution had to explain the ubiquitous variation of organisms. Darwin came to realize both that variation alone would not explain evolution and that a viable theory of evolution could be constructed with variation as an unexplained premise. These realizations were facilitated by Darwin's growing awareness of the sheer quantity of variation in nature and his doubts that variation was always adaptive (Gruber, 1974, pp. 159–61).

Once the principles of superfecundity and variation were firmly established as constraints, Darwin was able to appreciate the positive role of natural selection. His familiarity with artificial selection through domestic breeding may have sensitized him to this possibility.

The Malthusian insight resulted from the joint modification of several different constraints. Gruber has suggested reasons for Darwin's modification of these constraints, but it seems unlikely that Darwin would have succeeded in changing these constraints and arriving at his Malthusian insight if he had not had the overriding goal of explaining evolution. Extended effort characterized all of Darwin's work, both before and after the Malthusian insight. Indeed, the processes of verification and elaboration of the theory occupied most of the remaining years of Darwin's professional career. Darwin did not publish his theory of evolution until 1859, more than twenty years after the Malthusian insight.

CONCLUSIONS

We have proposed that five processes are central to the development of auctorive accomplishments in sci-
Scientific Creativity: Summary and Synthesis

In this section, we shall integrate conclusions from the previous chapters. First, however, let us briefly summarize these conclusions.

In chapter 1, we argued that creativity should be studied directly: creative persons must be identified on the basis of real-life products or performance, not on the basis of test scores. This argument was advanced on the logical grounds that test performance can be influenced by many factors unrelated to real-life creativity. Moreover, as is evident from the studies reviewed in chapter 2, no existing creativity test even comes close to achieving a one-to-one relationship with real-life creativity in scientists. Indeed, there is very little evidence in scientific areas for the criterion-related validity of most widely used creativity tests, especially those designed to measure divergent thinking abilities.

Therefore, we decided to focus on studies of persons who had demonstrated real-life creativity. Those whose
Creativity / discovery

The Psychology of Creativity and Discovery

Scientists and Their Work

Richard S. Mansfield and Thomas V. Busse

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