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The catalytic nature of science: Implications for scientific problem solving in the 21st century

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Abstract

This paper discusses key elements of scientific problem solving from a cognitive perspective in an effort to help scientists and engineers understand and manage their problem solving efforts more effectively. Toward this end, the Adaption–Innovation (A–I) theory of Kirton is reviewed and placed into the context of science in order to highlight its potential contributions and possible limitations. In particular, A–I theory is used to help explain different preferences for managing scientific structure, the need for a diversity of cognitive styles in scientific work, and the relationship between scientific progress and the paradox of structure. Directions for future research in this area and comments on the special implications of A–I theory for senior scientists and other technical problem solving leaders are also discussed.

Keywords: Adaption; Innovation; Problem solving; Diversity; Change

1. Introduction

‘If I have seen farther, it is by standing on the shoulders of giants’. Isaac Newton’s famous comment in a letter to Robert Hooke in 1676 illuminates the links that connect the contributions of scientists across time. The creative work of each individual builds upon the efforts of his[1] predecessors, both those who are well known and those who are not, moving the entire scientific enterprise forward. This cumulative chain of intellectual

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[1] For simplicity, ‘he’ is used to indicate ‘the individual’ in this article. Please read he/she, his/her, etc. as appropriate throughout.

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development has been in place since the beginning of human civilization, with a pattern intricately woven into the fabric of human progress. Each perceived opportunity, once successfully managed and exploited, becomes the stepping stone for more opportunities and more successes. In simpler terms, as we solve one problem, we introduce more (often unwittingly) that will need to be solved in the future. In effect, the number of problems that we face as a scientific community is growing exponentially as a direct result of our success as problem solvers. The complexity of these problems is also increasing, as more variables are discovered and the intricate relationships between them become apparent. In some instances, scientists are forced to span multiple disciplines as they search for solutions [1], and the implications of each solution reach farther and deeper with each succeeding generation.

As we examine this progression, we may well ask: What are the specific factors that drive and enable our problem solving? That is, what are the catalysts to scientific progress? In answer, we find that to some degree, the solutions themselves catalyze our problem solving, providing us with new theories (e.g. quantum theory) and new tools (e.g. the personal computer) that enable us to solve problems we would never have dreamed of solving just a few decades before. Strictly speaking, these theories and tools are not true catalysts (in the long term, at least), since almost without exception, they are eventually revised and updated as we use them. Nevertheless, in the short term, they do perform a catalytic[2] function, precipitating and/or intensifying the rates of reactions, whether they be reactions between chemical agents, physical forces, or human beings. Solutions, as catalysts, are key to scientific progress.

But there is a second, more fundamental catalyst to scientific problem solving that is largely ignored, even by its owners: the problem solving function of the human brain. In every normal, healthy brain across the species Homo sapiens, the same basic problem solving process is in operation [2,3]. Without this underlying cognitive process, opportunities present in the environment would remain unknown or ignored, known problems would remain unsolved, and new knowledge and experience would remain unused. We solve problems (scientific and otherwise) not only because we can do so or because we want or need to do so, but because we are enabled and driven to do so by our own inherent cognitive structure. The catalytic nature of science is no accident; it is a combined result of who we are and what we create.

In this paper, we explore the fundamental principles and application of a powerful model for problem solving called Adaption–Innovation (A–I) theory in an effort to help scientists and other technical professionals understand and manage their own problem solving efforts more effectively. We begin in Section 2 with a general discussion of scientific problem solving and its key elements. In Section 3, we review some general principles of Adaption–Innovation theory and their exposition in the context of science, including the separation of level and style, different preferences for managing scientific structure, and the paradox of structure [3]. In Section 4, we discuss the importance of cognitive diversity in problem solving, and in Section 5, we consider the management of

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[2] Catalytic: from the Greek kata- (intensive prefix) + lytikos (of, relating to, or effecting decomposition, dissolution, or release).

scientific change and the role and needs of the technical problem solving leader. Elements of theory are reflected in a number of useful examples, which are distributed throughout these sections. In Section 6, we provide a general summary of Adaption–Innovation theory and its potential for contribution within the scientific community. The article closes with commentary regarding the strengths and limitations of A–I theory, as well as suggestions for future research in the scientific problem solving domain.

2. Scientific problem solving

There are new expectations for today's scientists, and they are staggering: more solutions, to more complex and difficult problems, delivered at increasing speeds (with shorter and shorter timelines), and subject to increasing demands for higher accuracy with a decreasing tolerance for failure. In essence, as we succeed in solving each problem, our very solution of it makes the next round of problem solving even more challenging: we are victims of our own success. Our continued success, both as scientists in particular and as a species in general, depends upon our ability to handle such increasingly complex and difficult problems with greater efficiency and effectiveness than ever before. As Lienhard so aptly put it [4]: 'We live in a technology-dense world. The engines of our ingenuity are everywhere, and we are terrifyingly naked without knowing elementary things about how they work'.

One person's technical knowledge is no longer enough to accomplish this; the amount and diversity of information required is simply too vast. We must collaborate, bringing together the combined expertise and experience of several (or even many) individuals in order to solve the problem at hand. But in order to collaborate effectively, we will need to know more—and about different things. Collaboration is not instinctive in humans, and so as a start, we must learn how to collaborate, so that our very efforts at collaboration do not pose a greater problem than any one we have originally come together to solve.

Stated even more broadly: in order to handle the increasing diversity, complexity, and difficulty of the problems we now face, we need a diversity of problem solvers. To use these problem solvers wisely and well, we need to understand and manage the cognitive diversity inherent in the group. To achieve such an understanding, we must start with the problem solving individual and the catalytic cognitive functions of the most powerful scientific 'engine' we have at our disposal—the human brain. Only then can we begin to understand the dynamics of problem solving teams and their leadership.

2.1. The key elements of problem solving

In problem solving terms, we need to understand the links between the person (i.e. the problem solver), the process employed in problem solving, and the product or outcome of problem solving, all from a general perspective (as opposed to the specific activities or artefacts of a particular individual). These key elements of problem solving are shown in a simple schema in Fig. 1; a fourth key element, the environment, in which problem solving occurs, is also shown. These four elements of problem solving were formally identified by

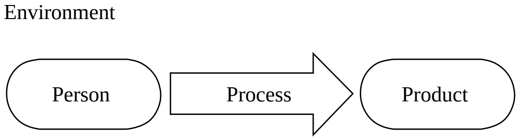

Fig. 1. The key elements of problem solving.

Rhodes in his early work on creativity [5], but thus far, scientists and their educators have not focused much on their study.

There are a number of possible reasons for this. First, the elements themselves and the gaps between them are large. Acquiring the knowledge and insight needed to understand even the most basic components, functions, and links within this schema requires a considerable investment of time and energy, both of which are already at a premium. Second, the links between the elements are far from clear. For example, there is no predictable cause and effect relationship between particular incidents in a person's life and the products that this person eventually creates, although we can safely assume that the environment has some kind of impact on the whole proceedings. This ambiguity makes the study of problem solving even more challenging and complicated.

Finally, physical and life scientists (and engineers as well) tend to be wary of the social sciences, which they view as 'soft' and imprecise. With the current confusion surrounding terms like 'creativity' and 'innovation', one really cannot blame them [3,6]. Nevertheless, ill-defined, complex, and challenging problems without predictable solutions are not unknown (or even unfamiliar) to scientists and engineers, and the risks of not understanding the links between the elements of problem solving are too great: we must persevere. If we do, we stand to gain critical insight into the inner workings of problem solving, and through it, increased predictability and control over scientific processes and their outcomes. If we do not, the competitive advantages we currently enjoy, the associated benefits to society, and even the continued growth of the scientific disciplines are all at risk.

Some outstanding pieces, which help fill the gaps, do exist, but as with the elements themselves, these also tend to lie on the periphery of the interest of most scientists and their educators. One well-known example is the work of Kuhn, the eminent philosopher of science who provided a clear sense of the link between a general scientific process and its outcomes (products) in his analysis of the structure of scientific revolutions [7]. Cohen has made similar important contributions, also with regard to the progress of science in general [8] and the works of several famous scientists (e.g. Isaac Newton [9]) in particular. Rossman's research into the psychology of invention [10] provides an insightful perspective on the links between a general class of problem solvers (inventors), the problem solving processes they employ, and the environmental factors that influence them.

On a specific level, biographers and historians of science continue to provide us with detailed and often fascinating glimpses into the lives of particular scientists and their discovery or invention of specific theories and artefacts [11–15]. These accounts are useful in a historical sense, but few generalizations (if any) can be made from them about scientific progress as a whole: the diversity of the human species is simply too great, and such an inductive approach cannot possibly be comprehensive. In order to understand the key elements of problem solving and the links that connect them, we must look deeper into the general nature of the problem solving process.

3. Adaption–Innovation theory: a promising approach

A significant, though less well-known, contribution from the field of psychology combines breadth and precision to bridge the gap between person and process in highly practical and particularly insightful ways. This contribution is the Adaption–Innovation theory of Kirton [3]. Kirton's aim is to understand human progress in general: how it proceeds, the factors that influence failure and success, and how the human species can manage its own progress more effectively. The common ground between this aim and that of science is problem solving. A review of some of the general principles of Adaption–Innovation (A–I) theory and their exposition in the context of science will be helpful as a backdrop for further discussion on the future of scientific problem solving and the implications for the scientific problem solving leader. We begin with some basic concepts:

3.1. Separation of level and style

First, Adaption–Innovation theory is based upon the general assumption that all people solve problems and are creative (even if only in everyday life). In general, the human brain does not differentiate between these two activities; they both involve the generation and resolution of novelty. However, as individuals, our problem solving does differ: we each solve problems to a greater or lesser extent (i.e. at different cognitive levels) and in different characteristic ways (i.e. with different cognitive styles). These two variables are independent, a fact which Kirton and others have demonstrated ably through considerable research and analytical proof [3]. In practice, then, knowing something about the problem solving level of a person (e.g. their skills, experience, knowledge, status) tells us nothing about their preferred problem solving style, and vice versa.

Differences in problem solving style appear even at the highest levels of intellect, as observed in the activities of Enrico Fermi (Nobel Laureate) and Leo Szilard (a member of the National Academy of Sciences). Both indisputably brilliant men, Fermi and Szilard collaborated (though with difficulty) in bringing about the first controlled nuclear chain reaction in 1942. Their characteristic approaches to problem solving could hardly have been more different. As described by Lanouette [16], Fermi was a rigorous academic and gifted experimentalist, who 'would not go from point A to point B until he knew all that he could about A and had reasonable assurances about B'. Szilard, on the other hand, dabbled in many subjects, 'shunned manual labor in favor of brainstorming', and 'would jump from point A to point D, then wonder why you were wasting your time with B and C' [16]. As we shall discover below, Fermi's highly structured thinking style was indicative of a more adaptive approach to problem solving, while Szilard's looser cognitive strategy typified a more innovative problem solver; both styles were necessary for the ultimate success of the project.

The separation of level and style is more important than one might initially suppose, particularly with regard to the formation and facilitation of collaborating teams. In creating a team for a particular task, for example, it is important to anticipate both the technical knowledge (i.e. cognitive level) that will be necessary to complete it and the cognitive styles that will be required throughout the problem solving process—a consideration that few problem solving tasks receive in sufficient measure. We typically take great care to assemble a team whose breadth and depth of technical expertise provide ample coverage of a problem's domain, but we are less meticulous in considering the cognitive strategies that will determine how ideas are formulated, analyzed, and developed throughout our task. In other words, we underestimate the importance of identifying the appropriate cognitive styles required for success and coordinating the effort that will be required to manage them. Such over-reliance on intelligence and other level characteristics (e.g. experience, skills) without appropriate consideration for style can lead to significant conflicts, as described by Hiltzik in reference to the scientists of Xerox PARC [17]. We will return to this example in a later section, but for now, let us consider in detail how cognitive styles might be described.

3.2. Describing and measuring cognitive style

Adaption–Innovation cognitive style falls along a continuum, ranging from highly adaptive on one end to highly innovative on the other. In practice, A–I cognitive style is measured using the Kirton Adaption–Innovation inventory (or KAI), a highly validated instrument that has been broadly applied across disciplines [3]. In addition to its high psychometric standards, it also does its job compactly and neatly. It is important to emphasize that the distinction between adaptive and innovative preferences is not a dichotomy, but a spectrum, the significance of which is best seen when the characteristics of different individuals are compared, rather than looking at the absolute position of any one person along the continuum. Thus, it is better and more accurate to describe individuals as 'more innovative' or 'more adaptive', rather than labeling them strictly as 'adaptors' or 'innovators' (although this is sometimes more convenient linguistically). Every individual is more adaptive when compared to some people and more innovative when compared to others.

It is also important to note that cognitive style is not behavior. Research shows that preferred style is stable, fixed early in life (at least by early teens), and does not readily change with time [3]. Behavior, on the other hand, is flexible and will sometimes be in accord with preferred style, while other times it is not. In general, actual behavior is a combination of preferred style and learned coping behavior. Coping behavior comes at a cost (extra effort) and must be switched on by insight (of need) and maintained by motive. Despite their differences in style, for example, Fermi and Szilard learned to collaborate in order to fulfill a mutual need—controlling the atom—but the strain between them was evident and sometimes required outside intervention in order to keep their projects on track [16].

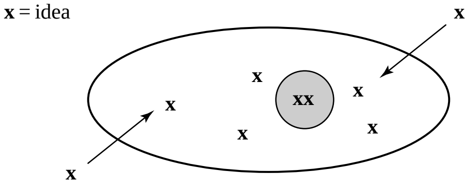

Fig. 2. Adaptive perspective on a scientific domain.

3.3. Different preferences for managing scientific structure

In general, A–I cognitive style can be described in terms of the different ways that people prefer to manage structure. In particular, the more adaptive prefer more structure when problem solving, with more of it consensually agreed. The more innovative, on the other hand, prefer less structure when problem solving, and they are less concerned with obtaining consensus around it. The impact of these differences is significant (and can be quite dramatic) at the individual level (e.g. Fermi vs. Szilard, Edison vs. Tesla), as well as in the scientific problem solving performance of teams.

Because of their different preferences, adaptors and innovators view scientific domains, their core concepts, and their respective boundaries differently. This is shown in Figs. 2 and 3, where in each case, the large oval represents the boundary of a specific scientific domain, which might be as broad as physics, or more specific, such as multibody dynamics or lumped parameter systems. The shaded circle represents the core of the domain, that is, those fundamental theories, assumptions, and concepts upon which the domain is based. Each ‘x’ represents an idea generated in the solving of a problem that is related to this domain.

Both adaptors and innovators are well aware of a domain’s core; it is a ‘fixed target’ upon which they can generally agree. Their responses to it are quite different, however. The more adaptive are drawn to the core, using it as a set of guidelines to be exploited in generating new ideas. Thus, more of their ideas tend to lie closer to this core; the most adaptive, in fact, prefer to stay as close to the center of the core as possible (Fig. 2). The more innovative, however, avoid the core, seeing it as cluttered territory in which they are less likely to find something ‘interesting’. Thus, their ideas tend to lie at a greater distance from the core, incorporating elements from other parts of the scientific domain (or even outside it) that may not be considered sound by their more adaptive counterparts (Fig. 3).

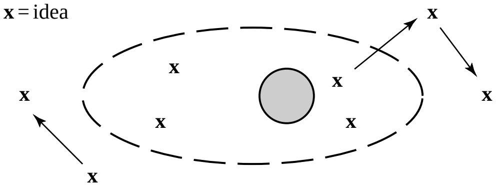

Fig. 3. Innovative perspective on a scientific domain.

The boundary of a given scientific domain is harder to define than its core, since it tends to shift and change dimensions as the domain progresses. Even without an explicit definition, however, adaptors and innovators view boundaries differently. The more adaptive problem solver tends to see the definitions of or constraints associated with a particular scientific domain (i.e. the boundary) as relatively solid. He prefers and tends to stay inside this boundary if possible. Conditions may lead this person to cross the boundary, however, or it may happen by accident, and he suddenly finds himself in new and unfamiliar territory. When this happens, the more adaptive person often becomes doubtful (even if he generated the idea that has taken him outside the domain) and moves back inside the domain's boundary to 'safer ground', as shown by the arrows in Fig. 2. Adaptors initiate creativity as often as innovators, but they prefer to do so within the given domain rather than at its edges.

More innovative individuals, in contrast, tend to view the boundary of a scientific domain as flexible or uncertain, if they recognize its existence at all (note the dashed oval in Fig. 3). When conditions lead them to cross the boundary, they are less concerned; in fact, the most innovative may intentionally move outside the domain and/or span several domains with their ideas. Ideas generated outside the domain's boundary by a more innovative person are just as likely to lead to more ideas outside the boundary, as shown by the arrows in Fig. 3. But there is another possible result of the innovator's fuzzy view of domain boundaries: since the more innovative are less concerned with where the boundaries lie, they may be just as likely to generate ideas that lie within them as outside them, although even the former offerings are not likely to fall too close to the core.

Kirton has provided some informal descriptions of the general characteristics of adaptive and innovative problem solvers in [18]; some of these are repeated in Table 1 for convenience. Note that any stage of any problem solving process can be characterized by an adaptive or an innovative approach. Consider the interwoven stages of theory and experimentation that define the Scientific Method, for example—theoretical tasks can be carried out more adaptively or more innovatively, with differing results. A more adaptive theoretician, for example, is more likely to focus on the fine details of a theory, modifying

Table 1
Some general characteristics of Adaption and Innovation [18]

The more adaptive problem solver	The more innovative problem solver
Seen as precise, reliable, efficient, prudent, and disciplined; approaches problems methodically	Seen as undisciplined, imprecise, and prone to tangential thinking; approaches problems from unexpected angles
Seeks solutions to problems in tried and understood ways	Questions a problem's assumptions; manipulates and redefines problems
Perceived as sound, conforming, safe, and dependable	Perceived as unsound, impractical; may even 'shock' his opposite
Challenges rules rarely, cautiously, and when assured of sound support	Often challenges rules and has little respect for past custom
Is an authority within given structures and systems	Tends to take control in unstructured situations
Solves problems through improvement and greater efficiency; works toward maximum continuity and stability	Is a catalyst to settled groups, irreverent of their consensual views; seen as abrasive and creating dissonance

and refining it in ways that make best use of the theory's underlying assumptions. A more innovative theoretician, on the other hand, is more likely to develop radically different elements of or applications for a theory by questioning its underlying assumptions or linking it with other tangential theories. Likewise, adaptive and innovative experimentation are both possible, with the former more likely to be methodically and consistently done and the latter more likely to include unexpected hypotheses and potentially 'shocking' conclusions. The elements in this array of descriptions do not, for Kirton, happen by chance, but in accord with underlying theory, as described below.

3.4. The paradox of structure

Let us now take our discussion of structure and style a step further and deeper. The concept of structure is fundamental to all scientists, both basic and applied. Physicists, for example, search for the underlying structure of matter as they attempt to explain how the world functions at the atomic level. Engineers develop structure on a larger physical scale when they construct mechanisms, bridges, circuits, and other artefacts. Biologists study the patterns of behavior that provide structure for the lives of various species. Indeed, the algorithms and theories any scientist creates are examples of conceptual structure, namely, the structure of ideas and assumptions that guide future actions.

Yet, within this search for a better understanding of the world, there is a hidden paradox, of which many scientists are intuitively, if not consciously, aware. Any structure (cognitive or otherwise) is both enabling and limiting at the same time, and balancing these opposing characteristics can be a considerable challenge. Kirton provides an insightful analysis of this paradox and the different ways that individuals manage it, based on their respective cognitive styles [3]. For example, in general, a more adaptive person is more likely to see the enabling features of the current system (model, theory) and is willing to tolerate its limits as long as some potential for enabling is still perceived to exist (Table 2). To this person, the introduction of a new system may carry with it too much risk for failure or potential for disruption, particularly if it is an untested or unproven one. In general, the more adaptive person is focused more on efficiency, rather than flexibility, and this goal is generally best served by keeping the current system in place (at least in the short term).

The more innovative individual, in contrast, is more likely to be attracted to the enabling properties of the new system, while generally ignoring (at least to some degree) its limits. In his eyes, the introduction of a new system is more or less required in order to solve the present problem, despite the fact that this change will undoubtedly introduce spin-off problems that have not yet been anticipated. These spin-off problems may be more adaptive in nature, or they may require an innovative solution themselves. In either case,

Table 2
Differences in managing the paradox of structure

	Current system	New system
More adaptive focus on	Enabling properties	Limiting properties
More innovative focus on	Limiting properties	Enabling properties

the more innovative problem solver is generally focused more on flexibility than efficiency and tends to be less attached to the system currently in place.

3.5. A brief case study of structure and style

Evidence of the different preferences individuals have for managing structure and its paradoxical nature can be found in the problem solving efforts of the scientists involved in the discovery and early development of the structural model for DNA [15]. In particular, we will focus here on the activities and views of the relatively more innovative James Watson and the even more innovative Francis Crick, in contrast with the more adaptive pair, Maurice Wilkins and Rosalind Franklin. In a broad sense, the relevant scientific domain for this example is molecular biology, but a smaller domain focused on techniques for analyzing molecular structures can also be defined.

The detailed structure of DNA was still something of a mystery in the early 1940 s, although the existence of the molecule had been discovered much earlier (by Miescher, in 1869). The X-ray diffraction technique was considered the standard approach for analyzing molecular structures at the time, and scientists were achieving increasingly more accurate results as they continued to refine this method. The first X-ray diffraction images of DNA were obtained by William Astbury in 1943, and in 1944, Oswald Avery and his associates showed that DNA could transfer characteristics known to be hereditary from one organism to another. X-ray diffraction was understood, proven, and known to be an effective analytical approach.

Nevertheless, another approach for studying the structure of macro-molecules was under development, and this was the use of physical models (which often resembled complex constructions of children's toys). In 1948, Linus Pauling used this (then) non-traditional approach to show that the structure of many proteins is an alpha-helix, a single spiral that resembles a spring coil. With Pauling's success, some researchers thought this new 'large-scale' physical approach might well be applied to other macro-molecules (including DNA), while many others continued to rely on X-ray diffraction to prove their theories.

As experienced members of the X-ray diffraction school and more adaptive by nature, Maurice Wilkins and Rosalind Franklin firmly believed that the structure of DNA (and other molecules as well) could be unlocked through the methodical accumulation and analysis of accurate X-ray diffraction data. In 1951, Wilkins and Franklin produced X-ray diffraction images of DNA in two forms. Franklin was also a first-class experimentalist and produced the best crystallographic images of DNA available at the time, yet the ultimate answer continued to elude these two scientists.

In that same year, James Watson and Francis Crick joined forces at Cambridge University and began their work on the structure of DNA as well. Impatient with detailed experimentation (as the more innovative often are) and the limitations (as they perceived them) of the X-ray diffraction technique, they believed they could decipher the structure of DNA through physical model building, supported (when necessary) by the X-ray diffraction data of others. Their first attempt was unsuccessful due to their misinterpretation of some data presented by Franklin in a lecture; however, after correcting their error and later (somewhat illicitly) obtaining access to one of Franklin's

X-ray diffraction images, Watson and Crick proposed and built a double-helical model of DNA, which they published in Nature in 1953.

Even in this brief example, the contrasting approaches of the two pairs of collaborators with respect to one of the prevailing scientific paradigms of the time (X-ray diffraction as a standard technique) are clear. Wilkins and Franklin relied on the enabling features of X-ray diffraction to support their investigation, even in the face of alternate suggestions from within their local scientific community, while Watson and Crick embraced the 'new' method of physical model building in an attempt to circumvent the limitations of X-ray diffraction to which they were more highly sensitized. In the end, Franklin left Wilkins' laboratory to study viruses, but Wilkins spent seven years verifying (via X-ray diffraction) the hypothetical model that Watson and Crick had constructed—work finally completed only with the advent of computers in the late 1950 s. Watson, Crick, and Wilkins were jointly awarded the Nobel Prize for Physiology or Medicine in 1962 for their combined efforts.

4. The importance of cognitive diversity

One practical distinction and outcome of the style preferences described in the preceding sections is the different views of problems and the solutions that result. In general, the more adaptive tend to refine current structure, solving the problem in the process, making things work better. The more innovative, on the other hand, tend to change the structure first, and then solve the problem using the new structure. They strive to make things work differently. These differences and their implications beg the question: which is the best approach to problem solving, Adaption or Innovation? If we look to the popular press, the current trend seems to preclude any Adaption, emphasizing Innovation alone as the desirable solution for all problems (e.g. 'we must think outside the box', 'Innovate or die!').[3]

But such an approach makes no more sense than having a toolbox which contains only a hammer and expecting every repair job to involve only nails. Different types of problems require different types of solutions, and different approaches and resources are needed to reach those solutions. From an objective scientific perspective, the solution to any problem should never be based solely on which approach is currently the most popular or the most familiar. In addition, when considering the ill-defined, complex, and challenging problems with which the scientific community is frequently faced, it is highly likely (if not a certainty) that different degrees of Adaption and Innovation will be required at different stages (or even within a single stage—e.g. testing) in the process of solving a single problem.

If we look back within the history of science, we can see evidence of this fact in the development of two fundamental scientific frameworks: the periodic system of the elements [19] and the heliocentric model of our solar system [20]. In addition to extended periods of time and high levels of intelligence, both of these monumental tasks required

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[3] It is a delicious irony that many high level, high innovators can become trapped in their own "box" (called "innovation") by believing that they are the only people who are creative – a thought that is hardly conducive to better team collaboration.

scientists of different cognitive styles. In the following subsections, we explore these two examples in more detail.

4.1. The periodic system (and table) of the elements

In the development of the periodic system of the elements and its associated periodic table, Dmitri Mendeleev is perhaps the most famous contributor, but he was far from alone in the effort. Doebereiner introduced his Law of Triads in 1829 (a forerunner to the concept of chemical groups), and Newlands proposed the Law of Octaves in 1864, a refined model of elemental periodicity based on atomic weights. Mendeleev's version of the periodic table (developed in 1869) left gaps for as yet undiscovered elements, the physical and chemical properties of which he predicted with remarkable accuracy. In addition, he placed some elements in the seemingly 'wrong' groups and/or in reverse order of atomic weight relative to the prevailing conventions of the day.

But neither Mendeleev nor the others mentioned above could have made their innovative contributions if other, more adaptive scientists had not first provided them with accurate details about the elements themselves (i.e. their atomic weights), details obtained (in this case) through methodical and highly structured experimentation. Two of the best known of these experimentalists are Berzelius and Cannizzaro, who published their results in 1828 and 1858, respectively. It was Cannizzaro's data, in fact, that Mendeleev arranged so artfully in the pattern that would direct the investigations of research chemists for years to come.

For there were many more elements to be discovered and meticulously measured in the decades to follow, including, for example, the noble gases (William Ramsey, 1894). Then, in 1914, Henry Moseley determined the atomic number of each element and modified the periodic law and table to arrange the elements according to this variable, rather than by atomic weight. This high level, adaptive refinement (which required both experimental and theoretical efforts) resolved the so-called 'inconsistencies' within Mendeleev's table, while confirming his radical hypotheses. By the 1930 s, even more elements had been identified; the heaviest of these were located in the main body of the periodic table. Glenn Seaborg, while working with Enrico Fermi on the Manhattan Project, 'plucked them out' and established the actinide series, which later permitted the proper placement of various manmade elements, thus changing the form of the table once again. Similar to Mendeleev, Seaborg challenged the prevailing paradigm with his hypothesis, which was later proved correct and earned him a Nobel Prize. At the time, however, he was discouraged by his colleagues from taking this unconventional stand.

At this writing, there are still gaps in the periodic table, which chemists and physicists are working hard to fill; the development of the periodic system (and table) of the elements is not complete by any means. It is interesting to note that the exploration of the relationships expressed in the table has lead to many new hypotheses about the structure of the atom, some of which may seem quite fantastic at first glance (e.g. superstrings [21]). Are we on the brink of another innovative restructuring of the atomic model? Perhaps or perhaps not, but of one thing we can be sure—any innovative new model that is introduced will require extensive adaptive efforts (particularly in testing and refinement) within the altered paradigm, before it and the suggested changes that have altered it are ever fully accepted by the scientific community at large.

4.2. A model for our solar system

In a similar fashion, the development of the heliocentric model of the solar system required both adaptive refinement and innovative redefining of existing scientific paradigms. As a starting point for this brief history, we begin with Aristotle, who proposed a geocentric model of the solar system (c. 350 BC), in which all the so-called planets (including the sun and moon) orbited the earth on perfect crystalline spheres. Ptolemy (c. AD 100) ensured the continued survival of this theory by fitting it to a sophisticated mathematical model (adaptively adding more structure). Because simple spheres were not enough to account for all the motions of the planets (e.g. retrograde motion), Ptolemy also added a variety of planetary mechanisms (e.g. epicycles, deferents) in order to explain the mounting astronomical data, which was becoming more and more accurate as new measuring devices were invented.

Despite its shortcomings, this model prevailed for approximately 1400 years, until, in the early 16th century, Nikolaus Copernicus was asked (by the Church) to explain the apparent anomalies in the motions of the planets with a simpler model, closer in concept to the original plan proposed by Aristotle. Copernicus came to the conclusion that there was a better way to explain things—viz, a heliocentric solar system with a moving earth. He retained Aristotle's circular planetary orbits, however, and in order to account for the apparent changes in planetary speeds and directions, he also used a good number ($\sim$90) of Ptolemaic epicycles. Despite its flying innovatively in the face of the prevailing geocentric paradigm, Copernicus' model was used to reform the Church calendar in 1582.

In the meantime, Danish astronomer Tycho Brahe (1546–1601) worked on the assumption that astronomy would progress through the extensive (and highly adaptive) collection of very accurate astronomical observations. He developed new and better instruments for viewing the heavens, and as a result, he was able to measure celestial positions with much greater accuracy than any other astronomer of his time. Still, Brahe could not accept a fully Copernican system (it was too innovative for his liking), so he proposed a compromise. In Brahe's model, all the planets except the earth orbited the sun; the sun and other planets orbited the earth, along with the moon.

Kepler (1571–1630) was Brahe's assistant, and upon the latter's death, inherited his extensive records. From these vast arrays of data and using meticulous mathematical methods, the relatively adaptive Kepler was able to formulate his three laws of planetary motion, which would later be improved upon by Newton, whose laws of motion were applicable to objects on earth and in the heavens. In the same timeframe, Galileo used a greatly improved telescope to observe the sun and planets; his startling observations and highly innovative conclusions forever refuted the 'wisdom' of Aristotle and cost Galileo his freedom (at least for a time).

4.3. Conclusions

Considering these examples (and many others), we are left with the undeniable conclusion that there is no 'best' cognitive style in any absolute sense, just as there is no one dominating level (skill or discipline) that can solve all aspects of a complex problem. We must design methods and solutions to fit each problem and the objectives associated with it, and to do so will require the strengths of individuals from many positions along the A–I style spectrum. Adaptors are no better than innovators at using their creativity, solving problems, or making decisions, and vice versa. We must use every nuance of every cognitive style to its own best advantage and to ours as a discipline, just as we must use every appropriate skill.

5. The management of diversity and scientific change

Cognitive style is only one form of cognitive diversity, which, according to Kirton, also includes cognitive level, motive, and (perceptions of) opportunity [3]. Put into context, Kirton describes the links between these forms as follows: in order for a person or group to progress (indeed, to survive), they must perceive all relevant opportunities (i.e. determine which are germane and concentrate on those), generate the motive to exploit what they perceive, and deploy the required levels (capacities) and the appropriate styles to solve each specific problem. This situation is poorly understood and often mismanaged. Unfortunately, we tend to perceive and treat differences of style as differences of level (typically lower and their owners as inferior); this is certainly a poor beginning for collaboration.

In collaboration, our diversity is simultaneously an advantage and an added problem, an example of the paradox of structure in its own right. Kirton describes this situation succinctly in terms of problem A and problem B [3]: when we come together to solve a problem (problem A), we immediately inherit a second problem, that is, how to manage each other (problem B). Successful groups spend much more effort on problem A than on problem B. The balance between these two problems does not take care of itself, however, it must be managed wisely and well. Otherwise, even if we serendipitously find ourselves in a group within which the dynamics seem to be naturally smooth, a mismatch between the strengths of the group and the requirements of the problem may still occur.

5.1. Problem solving leadership

Most, if not all, senior scientists must fulfill the function of a leader within their laboratories, their departments, and/or the greater scientific community. For a long time, we have searched (vainly) for ideal leaders who can, with the help of their teams, solve specific arrays of problems with guaranteed success. But with the immense array of problems we now face in science, as well as their increasing complexity, it is not possible for any one leader to know enough personally to arrive at all the answers. Instead, the entire team needs to solve the problems, with the help of capable and knowledgeable leaders.

Today’s problem solving leaders need to manage minds as well as matter, knowing how to inspire and help the different members of a team collaborate effectively, using the teams’ entire range of diversity (of level, style, and motive) to solve the problems they face. For this to occur, the problem solving leader needs to understand three things:

1. the theory and practice of problem solving,
2. the problem solver (their key resource), and
3. the ‘domain specific’ knowledge and experience appropriate to the problem in hand.

In other words, within science (as elsewhere), we need a new type of problem solving leader, one who knows enough about the current problem to hold his own in a team (however broadly defined), enough about the problem solving process, and enough about diverse problem solvers to get the team (not just himself, with some help) to solve the problem. This added burden is not trivial, but it is ultimately necessary for our continued success.

In science, as in any other discipline, a diversity of problem solvers is required to solve a diversity of problems. We need to understand the full range of diversity we have so that we can manage change more effectively, planning and coordinating the transitions between ‘evolutionary’ and ‘revolutionary’ science, gathering and allocating the human resources we need, where and when they are needed—all this, rather than reactively responding when we suddenly realize that ‘the way we have always done things’ (whether this is more adaptively or more innovatively) no longer works. Managing diversity is the key to managing change; it needs to be taught and practiced.

5.2. A short walk in the PARC

The many challenges of managing cognitive diversity and scientific change can be seen in the early history of Xerox PARC (Palo Alto Research Center) [17], established in 1970 to define the ‘architecture of information’ through cutting-edge research in computing and solid-state physics. The minds gathered at the PARC in those formative years were certainly some of the best and the brightest of their time; there is little doubt that they were all high level. From a style perspective, they were much less homogeneous and seemed to span a good portion of the A–I spectrum. As with any structure, this intellectual configuration both helped and hindered the development of new technologies at the PARC, as it served simultaneously both to inspire and irritate those attempting to manage the enterprise.

Charles Thacker, for example, was known for his highly detailed design work that optimized efficiency and avoided ‘biggerism’ (systems overloaded with unnecessary components). Known to his colleagues as ‘the engineer’s engineer’, Thacker was the lead hardware expert behind the Alto computer and appears to have been one of the more adaptive members of the original PARC staff. Butler Lampson, a top expert in operating systems design and another major contributor to the Alto, exhibited a similar style with his focus on ‘incremental things’ and a preference for taking measured steps (rather than blind leaps) on the road to technological success. These two ‘inspired engineers’ were instrumental in transforming the equally inspired but not necessarily concrete visions of their more innovative colleagues into reality [17].

Robert Taylor and Alan Kay were two such colleagues. Taylor, the first associate manager of the PARC's Computer Science Laboratory (CSL), was admired as a 'master motivator of top research talent', with an eye on the technical horizon and a penchant for bending the rules; he could also be highly abrasive and showed little respect for those with a less innovative outlook. Kay's innovative behavior was even more pronounced than Taylor's; he had a proclivity for startling, 'visionary' ideas, and he formed the like-minded Learning Research Group (which even Taylor called 'the lunatic fringe') to support them [17]. Taylor and Kay's intellectual kinship was a vital force in shaping the PARC's future, but an analysis of their history suggests that they also caused their more adaptive colleagues (e.g. Lampson and Thacker) considerable stress.

Such variations in style, compounded by an intense, competitive environment born of highly motivated, high intellects working in close proximity, created many challenges for the PARC's upper management. As an example, Jerome Elkind, manager of the CSL, tried to serve as a buffer between Taylor and the other lab chiefs, but it was a nearly impossible task. Eventually, both Taylor and Elkind left the facility under uncomfortable circumstances. Looking back, we can see where some of the systemic weaknesses in PARC management lay: (1) insufficient understanding of problem solving and its key variables, and (2) scant appreciation for the problem solver as an individual whose style both enables and limits every problem he undertakes (the paradox of structure once again). Attention was focused almost entirely on level (e.g. on hiring the 'smartest people around'), which—while useful and necessary—is not enough to guarantee success.

One conclusion that we might draw from this example is that if these high level thinkers had known more about problem solving theory and practice before they formed their groundbreaking collaborations, they might have been better able to foresee the advantages as well as the problems of managing their diversities—and managed themselves more effectively as a result. Creativity may either solve the problem and change the paradigm as a result of using it (Adaption), or alter the paradigm first in order to solve the problem (Innovation). Which approach is best depends on the nature of the problem, not the mode that is currently fashionable.

6. Summary: some key points for scientists

In summarizing Adaption–Innovation theory and its potential for contribution within the scientific community, several key points deserve special emphasis. First, understanding the separation of cognitive level and cognitive style, as well as their necessary managed interaction, is critical for the appreciation and management of cognitive gaps that may occur between individuals and/or groups, and between individuals or groups and the problems they must solve. As well-educated individuals, we are accustomed to evaluating and coordinating the level resources of ourselves and others (e.g. technical expertise), but the need to evaluate and coordinate style resources has been, until now, intuitive at best and often muddled.

Second, recognizing the value of and need for both Adaption and Innovation is significant. Scientific discovery and development are not restricted to 'breakthrough thinking', but also require methodical work to refine ideas and make them viable. On the other hand, an innovative idea may be needed to find the spark that ignites a scientific discovery process, particularly in times when existing methods or concepts have outlived their usefulness. Rarely in solving a large and complex problem can either Adaption or Innovation predominate; A–I theory helps to put the need for balance into perspective.

Third, the exposition of the paradox of structure is of particular importance to the scientific community. It provides a model for understanding the balance between predictability and flexibility within the problem solving process, and ultimately, it can be used to explain the nature of scientific progress in simple terms: every scientific idea, concept, or model is an intellectual structure. It is defined by its boundaries, the elements that constitute its content, and the relationships that exist between those elements. As an idea progresses, it is initially enabled by its structure, but gradually, it becomes limited by the very structure that has made it effective thus far. Consider, once again, the geocentric model of the universe proposed by Aristotle and refined by Ptolemy and others (Section 4.2): it lasted for nearly 2000 years and was very useful in the prediction and interpretation of many heavenly (and earthly) events. Ultimately, however, it could no longer explain satisfactorily the mounting collection of increasingly accurate astronomical data, and scientists of the time began to question its efficacy.

When the limitations of the current structure become too great, the structure is gradually loosened so that it may be rebuilt in new forms that allow more opportunities for explanation and prediction. Many of these new forms will fail, but some of them are vital to further progress. Recall the efforts of Copernicus: he (re)introduced fresh assumptions into the Ptolemaic model of the solar system (e.g. that the earth moved), but he did not fully reject many of the astronomical devices that Ptolemy had put into place (e.g. epicycles), thereby loosening the structure without completely destroying it. Copernicus' new model, while far from perfect, was nevertheless a catalyst for the natural philosophers who came after him.

Once loosened, the new structure is experimental, unproven, and still inefficient, a condition which can only be corrected by improving and tightening the structure once again. To continue our example: while it solved a number of the problems of its day, the Copernican model was not completely accurate. It required the accurate astronomical measurements of Brahe and the methodical calculations and refinements of Kepler to eliminate the epicycles at last and provide a better match between theoretical predictions and experimental data.

This repeated process of 'tightening' and 'loosening' an idea, theory, or model as it develops over time is the paradox of structure in action. We can learn a great deal by recognizing and observing this pattern for what it is—a catalytic spiral of change in which science advances as it alternates between revolution and evolution, between paradigm-cracking and paradigm-refining phases, neither one ultimately more important than the other, both absolutely necessary in order for scientific progress to occur. In short, the paradox of structure applies to the scientific process as much as it applies to the human cognitive process; we stand to benefit by appreciating the links between the two.

7. Conclusions and next steps

If we recall the schema of Fig. 1, we see that Adaption–Innovation theory has made notable progress in linking the person with the process from a general perspective. Kirton's framework for understanding problem solving (in all its forms) is sound enough to enable prediction and flexible enough to support expansion and revision; as Kelly points out [2], these are two characteristics of any good theory. In particular, A–I theory explains clearly how people solve problems, eliminating much of the confusion found in the literature devoted to creativity. It identifies and places the variations in human problem solving in a larger context and provides a model for the management of diversity and change. Finally, it is non-pejorative, demonstrating the value of all cognitive styles across the spectrum. Scientists, engineers, and other individuals in senior positions (whatever their discipline) who are looking for ways to understand and facilitate change will find this theory valuable in their efforts. For additional reading on A–I theory, the KAI, and their application across a wide range of disciplines, see Refs [3,18,22].

While Adaption–Innovation theory is powerful and practical, there are limitations and challenges to its use. First, it is itself an innovative contribution from several perspectives. Within its own domain of psychology, for example, A–I theory departs from many current views of creativity in a number of ways (e.g. that all people are creative, rather than a select few). And, as applied to science and engineering, using A–I theory in any great depth is highly non-traditional in itself. As previously noted, most scientists and engineers give little thought to the way in which they solve problems; rather, they tend to focus only on whether they have solved them or not.

Fortunately (both for potential users and the theory), A–I theory is supported by quite a bit of structure, including a body of research results and a community of certificated practitioners, which will make this integration task easier. This support is far from complete, however. All general theories need testing, at least by application to specific needs. Considering the time scale for A–I theory (it was first introduced only 25 years ago), it could not possibly be fully tested yet. Its generality and breadth necessitate further investigation: the broader a theory, the more the key elements need to be tested, both in analysis and application. And to test this theory in its breadth will require people from many different disciplines, which will do little to shorten the process.

Thus, further development and application of A–I theory are needed, both to refine the theory and to provide additional support and practical proofs as new questions are raised. In testing the truth, value, and specific applicability of this theory (and its support to date), we need to learn more about the management of the problem solving process. In addition, we need to understand better: (a) the participating problem solvers in the specific context within which these problems have arisen; (b) how the individuals manage their diversity to achieve success; and (c) how best they can be led. In science, for example, we need to explore the impact of cognitive style in the various stages of the discovery process. In engineering, we need to perform similar studies with respect to the processes of design and invention. Further exploration of the link between a general process and its resulting products is also needed to complete the path from person to product (in reference to Fig. 1). These are no small undertakings, but they are necessary steps on the way to understanding and modifying our own problem solving behavior to everyone's best advantage.

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