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A Meta-Analytic Approach (Commentary on Simonton, 2009)

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ABSTRACT—Innovations in science can be divided into at least four major types: radical revolutions (such as Copernican and Darwinian theory), technical revolutions (led by scientists such as Newton, Lavoiser, and Einstein), controversial innovations (for example, Semmelweis's theory of puerperal fever), and conservative innovations (eugenics and various vitalistic doctrines). Biographical predictors of support for scientific innovations are distinctly different depending on the type of innovation, as are the predictors of who initially engineers such innovations. A meta-analytic approach assessing each new scientific theory according to its salient features (including epistemological, ideological, and technical attributes) is required to make sense out of the varied predisposing factors associated with the origins of these innovations. These predisposing factors are not neatly classifiable in terms of Simonton's (2009, this issue) hierarchical model of domain-specific dispositions, although this model is applicable under some conditions. Instead, the principal sources of scientific achievement are largely a product of person-by-situation interaction effects that are dictated by the nature of the particular innovation.

Setting forth generalizations about the sources of scientific achievement is a challenging undertaking, especially if one seeks to test such theories using evidence drawn from the historical record. The difficult nature of such a project is exemplified by the striking diversity of innovations that have punctuated the history of science. As a consequence, what helps to explain one particular scientific innovation is often not useful in explaining others, as historians of science have long pointed out in their critiques of Thomas Kuhn's model of scientific revolutions (Ghiselin, 1972, Gingerich, 1975; Greene, 1971; Hoyningen-Huene, 1993; Kuhn, 1970, 1977; Sulloway, 1996).

Simonton (2009, this issue) has proposed a hierarchical model of domain-specific achievement in science and other fields. In particular, he offers three distinct explanations for how innovations arise during knowledge production. These three hypotheses hold that new knowledge originates from approaches and individual dispositions that are either typical of the knowledge domain in which they arise or are domain progressive or regressive, exemplifying attributes that lie higher up or lower down within a status hierarchy that extends from the humanities to the hard sciences. Although Simonton has suggested his own favorite from among these three hypotheses, namely, his domain-regressive alternative, he has done so in a tentative fashion and with due respect for contradictory exemplars.

REVOLUTIONS IN SCIENCE

When we examine the kinds of background factors that reliably predict support for, and opposition to, important innovations in science, we find that scientists who have first proposed and then extended revolutionary ideas are not necessarily the same sorts of scientists who have taken the lead during other revolutionary events. A good example is provided by Louis Agassiz's development of glacial theory during the 1830s. Charles Darwin

was initially skeptical of Agassiz's controversial ideas, as were other contemporary geologists, including Charles Lyell and Leopold von Buch. Yet, at this time, Darwin and von Buch were strongly sympathetic to the theory of evolution and hence had already shown evidence of revolutionary inclinations in their own scientific work. By contrast, some of the strongest supporters of Agassiz's glacial theory, such as William Buckland and Arnold Guyot, were vehement opponents of the theory of evolution. As for Agassiz himself, he also rejected the idea of evolution, and 2 decades later, after Darwin published the *Origin of Species* (1859), Agassiz was among the leading critics of Darwin's theory of natural selection.

A principal source of these inconsistent revolutionary allegiances lies in the fact that glacial theory was initially perceived by many scientists as a throwback to geological catastrophism (Boylan, 1998; Carozzi, 1966). In the 1830s, the scientific liberals of the day, including Lyell and Darwin, were doing their best to oust catastrophic notions from the geological profession in favor of Lyellian uniformitarianism. Lyell's uniformitarian approach was in turn was part of a broader effort to rid geology of religious influences based on the doctrine of a biblical flood. This historical example suggests that the epistemological and ideological contexts associated with new scientific theories tend to dictate which scientists are most likely to develop such theories.

Fortunately, some degree of predictability emerges from the diversity of innovations observed in the history of science. First, a bit of epistemological taxonomy is required to make sense out of the results. In my own previous research on this topic (Sulloway, 1996), I analyzed 28 major controversies in science, dividing them into four main classes: radical revolutions (such as Copernican and Darwinian theory), technical revolutions (including the

achievements of Isaac Newton, Antoine Lavoisier, and Albert Einstein), controversial innovations (such as Ignaz Semmelweis's theory about the causes of puerperal fever), and finally conservative innovations (consisting of eugenics and various vitalistic ideas celebrating the uniqueness of life). I based these classifications on a series of objective criteria, such as whether books about the new theory were ever banned by the Catholic Church's *Index Librorum Prohibitorum* (which defines most radical revolutions) and how often each of the 28 controversies has been described as a "revolution" by prominent historians and philosophers of science (Cohen, 1985; Hacking, 1981; Kuhn, 1970).

Independently of such formal historical criteria, these four classes of scientific innovations can also be distinguished by the kinds of background factors that predict individual receptivity to innovation. For example, radical scientific revolutions have tended to be supported by political and religious liberals, by younger scientists, by laterborns, and by people who have experienced high levels of parent–offspring conflict when they were growing up.¹ In general, these same four background variables cluster together as significant predictors of receptivity whenever new scientific theories have been highly controversial (as indicated by a low initial acceptance rate) and whenever such theories have spilled over into a broader debate among nonscientists. In addition, radical innovations are especially likely to be identified by historians and philosophers of science as having been major "revolutions" in science.

Other forms of scientific innovation attract recruits who are typically different from the scientists who have either initiated or been early supporters of radical revolutions. For example, less radical forms of scientific innovation show only a modest tendency to be endorsed by scientists who are socially liberal or laterborn. In addition, these nonradical

innovations are more likely to exhibit significant national differences in the adoption of new theories, indicating greater geographic localization than that found in radical revolutions. Being young, moreover, is a better predictor of support for certain kinds of nonradical events—particularly technical scientific revolutions—than it is for radical innovations, showing that professional experience plays a greater role when competing ideological allegiances are not involved.²

Controversial innovations in science are minor technical revolutions in many ways. These events tended to involve a smaller number of participants and were generally quicker to end debate over new theories. Finally, conservative innovations are largely the antithesis of radical revolutions in science, being supported by social conservatives rather than liberals and by firstborns rather than laterborns. In addition, age is only a modest predictor of the acceptance of conservative innovations, reflecting the fact that conservative ideas sometimes appeal to older scientists.³

On the basis of this review of the kinds of background variables that correlate significantly with attitudes toward scientific innovation, one can make a compelling case that all three of Simonton's domain-specific hypotheses hold true with respect to the early promoters of new theories. These three hypotheses tend to hold true, however, under very differing circumstances. For example, conservative innovations, including attempts to refute materialistic theories about life, have often represented epistemological attempts to return to earlier ways of thinking, as was the case with preformation theory. This biological theory, which was championed by Jan Swammerdam in the 17th century and by Charles Bonnet and Albrecht von Haller in the 18th century, held that embryos were already “preformed” within the mother and hence were not being developed, *de novo*, out of unorganized matter. The

doctrine of preformation was proposed in part to overcome the distasteful materialistic implications of epigenesis, the theory that eventually won out (Roe, 1981). From an ideological perspective, such conservative innovations have generally been regressive rather than domain typical or progressive, because they have often been antireductionist, rejecting concepts and methods drawn from domains located higher up in the scientific hierarchy. By contrast, radical scientific revolutions, which are typically associated with a reductionist approach associated with the progressive social attitudes of their advocates, appear to epitomize Simonton's notion of domain-progressive innovations. For example, these historical events have typically helped to bring about the overthrow of traditional social and religious values, as the Copernican and Darwinian revolutions did, and have sought to base scientific explanations exclusively on natural law. Nevertheless, because radical revolutions have tended to appeal to scientists who have experienced high levels of parent-offspring conflict, such events can also be considered domain-regressive, not progressive, as Simonton (2009) himself has suggested in his discussion of this particular developmental predictor.

What is needed to make sense out of these disparate historical findings is an organizational framework that distinguishes between the various epistemological, ideological, psychological, and social attributes that define the salient characteristic of each scientific transformation. A new scientific theory may turn out to be epistemologically and ideological progressive, like the Darwinian revolution, while at the same time being psychologically or socially regressive with regard to some of the key biographical dispositions that prompt support for such a theory. To explain the considerable diversity of innovations that are observed in the history of science, and especially to explain the sometimes striking differences among the biographical attributes of the innovators, we need

to embrace a broad meta-analytic approach to the problem (Faust & Meehl, 2002; Hunter & Schmidt, 1990). In short, we are facing a multidimensional statistical problem that is unlikely to yield results that hold uniformly true from one event to another or lie neatly on any single dimension of epistemological change.

INITIATORS VERSUS CONVERTS

Innovation and support for innovation are different forms of scientific activity, and I do not mean to blur this important distinction. My own database of biographical information on 3,896 participants in 28 controversies in science was not designed primarily to understand the sources of individual innovation—although it does, I believe, shed considerable light on these sources. It is nevertheless possible to adapt these biographical data to focus more directly on scientific innovators, rather than on their subsequent supporters and opponents. In the course of my 1996 study, I constructed a variable to identify the 91 “initiators” of the 28 scientific innovations I was analyzing. In doing so, I coded each scientist on a four-step scale (0–3) in terms of their individual roles in bringing about the specific transformation in which they took part. For example, I awarded both Darwin and Alfred Russel Wallace 3 points for having set forth the theory of natural selection, as well as for their subsequent contributions to the Darwinian revolution. Major pre-Darwinian evolutionists, such as Jean-Baptiste Lamarck and Robert Chambers, each received a score of 2, with a number of minor evolutionists, such as Bory de Saint-Vincent and Leopold von Buch, being given a 1. All other scientists, whether they supported or opposed evolutionary ideas, received a score of 0.

Although this four-step scale necessarily involves a degree of subjective judgment, it exhibits reasonable predictive validity. For instance, scientists who I rated highly as initiators in my sample tend to score highly on a composite measure of eminence, based on 19 scales: r

= .42 ($n = 2,909$, $p < .0001$; 15 of these 19 scales are drawn from Simonton, 1984). Similarly, my own four-step measure of initiators correlates .50 with the number of times each participant in my database is listed in the index to I. Bernard Cohen's *Revolution in Science* (1985), which provides a wide-ranging overview of revolutionary achievements in the history of science. A correlation of .50 between Cohen's citation patterns and my own scale for initiators is surprisingly large given that Cohen's 711-page book discusses not only revolutionary scientists, but also their most vehement critics, whose often sizable citation counts attenuate the correlation. In addition, Cohen's book reviews the published observations of numerous scientists, such as Auguste Comte and William Whewell, who happen to have written extensively about the advancement of science from a philosophical or historical perspective but who did not themselves initiate a scientific revolution and who, in some cases, strenuously opposed one.

Owing to the relatively modest number of individuals in my database who can be designated as initiators ($n = 91$), any effect sizes obtained when comparing this select group with other scientists will tend to be small, resulting in modest power to detect significant differences. Nevertheless, information on the status of initiators does tend to corroborate generalizations I have previously made about the early adopters of new theories. For example, social progressives such as Darwin and Wallace were decidedly more likely to initiate radical revolutions in science than were other participants in this same class of controversies ($r = .19$, $n = 545$, $p < .0001$). During the other three classes of scientific innovation, social attitudes generally played no role among the initiators ($r = -.03$, $n = 1,340$, $p = .27$ —; for the difference between these two effects, $Z = 4.37$, $p < .0001$).

Similarly, laterborn scientists were more likely to emerge as scientific initiators during radical revolutions than they were during other types of scientific innovation ($r = .17$, $n = 322$, $p = .003$, and $r = .01$, $n = 807$, $p = .87$, respectively—; for the difference between these two effects, $Z = 2.44$, $p = .01$). Firstborns such as Galileo, Kepler, Newton, Lavoisier, and Einstein had their greatest advantage as innovators during technical scientific revolutions, which have often required considerable mathematical expertise ($r = -.08$, $n = 499$, $p = .08$; for other types of innovation, $r = .07$, $n = 795$, $p = .03$; for the difference between these two effects, $Z = 2.62$, $p < .01$).

In a closely related vein, firstborns in this historical sample of 28 scientific innovations became significantly more eminent in the course of their careers than did their laterborns peers ($r = -.09$, $n = 1,278$, $p = .001$), indicating that firstborns had a modest edge in overall scientific achievement—a difference that is consistent with the well-documented relationship between birth order and intellectual performance (Kristensen & Bjerkedal, 2007; Sulloway, 2007; Zajonc & Sulloway, 2007). Such findings are consistent with the fact that, relative to other winners of the Nobel Prize, firstborns winners in science are overrepresented by a factor of 2.0 (Clark & Rice, 1982). Nevertheless, one should bear in mind that most Nobel Prizes are awarded for what Thomas Kuhn (1970) has described as clever “puzzle solving” within a normal science tradition, not for revolutionary breakthroughs, which are relatively rare events. Einstein, for example, received the Nobel Prize in physics for his discovery of the photoelectric effect rather than for his revolutionary ideas about special and general relativity, which were deemed too controversial and too theoretical for a Nobel award.

REVOLUTIONARIES AS DOMAIN-TYPICAL INNOVATORS

Another relevant finding about the 91 initiators of my 28 scientific innovations is that they tended to distinguish themselves in a large number of scientific fields more often than did other contemporary scientists ($r = .16$, $n = 2,712$, $p < .0001$). Nevertheless, they worked mainly in the field that was being transformed, rather than in a field above or below it in the science status hierarchy ($r = .06$, $n = 2,783$, $p = .003$, based on a binary contrast by field status).

To provide a more robust test of Simonton's domain-progressive hypothesis—which corresponds epistemologically with the tendency for science to advance by reductionism—I have created a measure that compares the overall field-epistemological status of each scientist in my database, judged in terms of Simonton's Comtean hierarchy, with respect to the field in which each innovation occurred. Hence, a scientist such as Darwin, who revolutionized natural history, is coded for fact that he also worked in geology, a field that was higher up on the Comtean hierarchy than the one he eventually revolutionized. On this measure, initiators were not significantly different from other participating scientists ($r = .02$, $n = 2,708$, $p = .38$). What this finding suggests is that reductionism—a domain-progressive epistemological strategy—probably explains only a modest proportion of the success achieved by past scientific innovators, who more often than not have prospered by a variety of domain-typical, rather than domain-progressive, strategies. Moreover, if most innovators have benefited from domain-typical strategies and from associated, domain-typical biographical attributes, then the notion of relative status within a domain hierarchy may be of limited value in explaining creative breakthroughs in science.

This is not to say that relative status is completely unimportant in determining revolutionary allegiances. Being young, for example, correlates significantly with support for

most scientific revolutions ($r = -.28$, $n = 2,400$, $p < .0001$). Being young, however, does not correlate with status as an innovator ($r = -.04$, $n = 2,400$, $p = .02$; for the difference between these two correlations, $Z = 9.03$, $p < .0001$, when using Meng, Rosenthal, & Rubin's, 1992, method). This discrepancy is enlightening. Relative to their youthful supporters, older scientists have a greater likelihood of developing a revolutionary alternative, most likely because of their superior knowledge about the relative strengths and weaknesses of the field being revolutionized. Compared with older scientists who have not yet seen the light, younger and less-experienced scientists find it easier to adopt the new alternative, probably because they do not have as great a professional stake in the reigning paradigm. In this regard, then, innovators in science tend to be domain-typical by age, whereas their earliest supporters tend to be domain atypical. (Whether one chooses to define these youthful supporters as being domain regressive or progressive depends on which aspects of age one wishes to emphasize.)

NEW THEORIES AND THEIR INTELLECTUAL NICHES

In the light of the collective findings from my study of 28 major innovations in the history of science, I believe there is a demonstrable need for a multifaceted perspective on scientific innovations—one that recognizes that there are many different ways in which innovations may arise and gain subsequent traction among their early adopters. In addition, a multifaceted perspective on scientific innovation tends to underscore the need for some of concepts that have proven useful in understanding innovations in the natural world. Like successful species in nature, successful scientists are often preadapted to important intellectual transformations. As a result, these scientists are able to seize more quickly on new conceptual niches and develop them in fruitful ways.

An evolutionary perspective on knowledge production has a venerable tradition going back to Campbell (1974), Hull (1988), and other scholars, including contributions by Simonton (1999) himself. In particular, an evolutionary perspective prompts us to be careful of how we apply the terms *progressive* and *regressive* when referring to innovations. For example, many successful species in nature have found new and successful niches by engaging in seemingly retrograde evolution. A dramatic example known to Darwin (1872) is the ascidian or sea squirt: a primitive, free-swimming vertebrate that, during its development, reabsorbs its notochord and spends its adult life in a vegetative state affixed to the ocean floor. It was evolutionary paradoxes of this sort that prompted Darwin to remind himself never to use the words *higher* and *lower* when referring to evolutionary outcomes (Secord, 2000). In the course of evolution, what seems lower, or regressive, is sometimes a progressive and superior result of successful niche exploitation.

As I have argued in this commentary, innovations in science seem to come in each of the three forms that Simonton's (2009) model specifies. In addition, the same episode of scientific innovation can exhibit disparate and even conflicting attributes—being progressive in ideology, for example, while at the same time being regressive in other attributes, such as predisposing biographical factors. This is why a meta-analytic approach to the problem of innovative strategies is likely to be essential for its ultimate solution. Moreover, every successful innovation can be usefully conceptualized as the product of person-by-situation interaction effects. With a meta-analytic approach to this problem, the search for moderator variables may well end up being more important than any of the main effects we succeed in documenting. In other words, the sources of scientific innovation need to be understood in terms of multifaceted performance niches that reflect differences in epistemology, individual

psychology, and social factors, as well as the broader historical context. During each particular scientific event, the most relevant sources of innovation will likely be determined by person-by-situation interactions between the salient features of the innovation and biographical attributes of the innovators.

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¹These and other generalizations about the sources of support for new scientific theories are documented in Sulloway (1996). Statistical tests are presented here only for new tests that I have conducted as part of my commentary on Simonton's (2009) article.

²For the role of social attitudes during the acceptance of radical revolutions, as determined by individual ratings of religious and political attitudes made by 94 historians, $r = .46$ ($n = 545$, $p < .0001$), and for other types of scientific events, $r = .13$ ($n = 1,341$, $p < .0001$); for the difference between these two correlations, $Z = 7.20$, $p < .0001$. For the role of birth order in the acceptance of radical revolutions, $r = .31$ ($n = 322$, $p < .0001$), and for other types of scientific events, $r = .14$ ($n = 807$, $p < .0001$); for the difference between these two correlations, $Z = 2.71$, $p = .007$. For the role of national differences in the acceptance of radical revolutions, $r = .11$ ($n = 711$, $p = .005$), and for other scientific events, $r = .23$ ($n = 2,217$, $p < .0001$); for the difference between these two correlations, $Z = 2.87$, $p = .004$. For the role of age in the acceptance of radical revolutions, $r = -.20$ ($n = 624$, $p < .0001$), and for other scientific events, $r = -.30$ ($n = 1,775$, $p < .0001$); for the difference between these two correlations, $Z = 2.29$, $p = .02$. During technical revolutions, the correlation between age and acceptance of the proposed innovation is $-.39$ ($n = 1,073$, $p < .0001$); for the difference between this correlation and that for other nonradical revolutions ($r = -.17$, $n = 703$, $p < .0001$), $Z = 4.94$; $p < .0001$.

³For the relationship between social attitudes and support for conservative innovations, $r = -.16$ ($n = 293$, $p = .007$), and for other scientific innovations, $r = .34$ ($n = 1,592$, $p < .0001$); for the difference between these two correlations, $Z = 8.07$, $p < .0001$. For the relationship

between birth order and support for conservative innovations, $r = -.08$ ($n = 195$, $p = .27$), and for other scientific innovations, $r = .24$ ($n = 934$, $p < .0001$); for the difference between these two correlations, $Z = 4.14$, $p < .0001$. For the relationship between age and support for conservative innovations, $r = -.11$ ($n = 362$, $p = .04$), and for other scientific innovations, $r = -.31$ ($n = 2,037$, $p < .0001$); for the difference between these two correlations, $Z = 3.67$, $p < .0001$. This commentary presents 41 statistical tests, 36 of which are significant. All 36 tests remain significant after being adjusted for the false discovery rate (Benjamini & Hochberg, 1995).