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Foresight, Insight, Oversight, and Hindsight in Scientific Discovery: How Sighted Were Galileo's Telescopic Sightings?

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Galileo Galilei's celebrated contributions to astronomy are used as case studies in the psychology of scientific discovery. Particular attention was devoted to the involvement of foresight, insight, oversight, and hindsight. These four mental acts concern, in divergent ways, the relative degree of "sightedness" in Galileo's discovery process and accordingly have implications for evaluating the blind-variation and selective-retention (BVSR) theory of creativity and discovery. Scrutiny of the biographical and historical details indicates that Galileo's mental processes were far less sighted than often depicted in retrospective accounts. Hindsight biases clearly tend to underline his insights and foresights while ignoring his very frequent and substantial oversights. Of special importance was how Galileo was able to create a domain-specific expertise where no such expertise previously existed—in part by exploiting his extensive knowledge and skill in the visual arts. Galileo's success as an astronomer was founded partly and "blindly" on his artistic avocations. The investigation closes by briefly discussing Antonie van Leeuwenhoek's similar creation of microscopic biology. This parallel case indicates that Galileo's telescopic astronomy was probably not unique as an illustration of how scientific discovery works in practice.

Keywords: discovery, hindsight, expertise, BVSR, Galileo

Galileo Galilei[1] is widely counted among the greatest scientific geniuses who ever lived. In Murray's (2003) historiometric evaluations of 1,445 significant scientists, Galileo scored 89, second only to Newton's 100. Although Galileo's contributions to physics were certainly stellar, his discoveries in astronomy are what really set him apart from other scientists of comparable greatness. For example, according to Murray's assessments Galileo placed fifth among 218 significant physicists, receiving a score of 83, with Isaac Newton and Albert Einstein tied for first place with scores of 100 each. However, among 124 significant astronomers, Galileo came in first, with a score of 100, followed by Johannes Kepler in second place with a score of 93. Galileo's top rating in astronomy matches not just those of Newton and Einstein in physics, but also the 100 points credited to Charles Darwin, Antoine Lavoisier, Charles Lyell, Leonard Euler, Louis Pasteur, and James Watt in the domains of biology, chemistry, earth sciences, mathematics, medicine, and technology, respectively.

What makes Galileo's astronomical observations especially striking is that every major discovery can be replicated by an amateur astronomer using a telescope purchased at a local toy store. Anybody can see for themselves the mountains of the Moon, the four main satellites of Jupiter, the phases of Venus, the rings of Saturn, the spots on the Sun, and the star clusters of the Milky Way.[2] Furthermore, Galileo's pioneering observations eventually spurred him to advocate overtly the Copernican (heliocentric) planetary system over the Ptolemaic (geocentric) system. His advocacy culminated in the 1632 *Dialogue Concerning the Two Chief World Systems*, a work that provoked a historic confrontation with the Roman Catholic Church. As a result, Galileo was forced to recant his Copernican beliefs and spend the remaining years of his life under house arrest. Forbidden to publish, Galileo's last great work, the 1638 *Dialogues Concerning the Two New Sciences*, was smuggled out of Italy to be printed in the Netherlands just 4 years before his death. Of course, Galileo is popularly depicted as the great scientific hero and his opponents as villains who ignored the obvious facts that could be plainly seen with their own eyes (e.g., Harris, 2010). How could anyone deny that the Moon had mountains or that Jupiter had moons?

However, the science and the history underlying Galileo's astronomy were far more intricate and nuanced than commonly portrayed. Galileo was not always in the right, and his enemies were not invariably wrong (Van Helden, 1989). In fact, Galileo's life and work amply illustrate what has been called the historical "fallacy of presentism," a kind of anachronism "in which the antecedent in a narrative series is falsified by being defined or interpreted in terms of the consequent" (Fischer, 1970, p. 135).

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[1] Although Galileo was actually his given or "first" name (his full name being Galileo di Vincenzo Bonaiuti de' Galilei), eminent figures in this time and place were often referred to by their first names. Another well-known example is Michelangelo (di Lodovico Buonarroti Simoni), a fellow native of Tuscany, who died in the same year that Galileo was born (1564). This convention does introduce some awkwardness in citing Galilei as the author of Galileo's works.

[2] Indeed, the author of this article verified every one of these discoveries when he was a teenager using a 40-power Newtonian telescope.

That is, the past is viewed through glasses heavily colored by the viewpoints of the present. A classic example is "Whig history," which is defined as the "tendency in many historians to write on the side of Protestants and Whigs, to praise revolutions provided they have been successful, to emphasize certain principles of progress in the past and to produce a story which is the ratification if not the glorification of the present" (Butterfield, 1931, p. v). In the specific case of Galileo, because the Copernican revolution ultimately won, his contributions to the overthrow of the Ptolemaic system are subsequently viewed as tremendously prescient and insightful—as strokes of pure genius.

Psychologists have their own concept for what might be happening in such instances, namely, hindsight bias (Fischhoff, 2007). Events or outcomes that have low a priori probabilities suddenly acquire high post hoc probabilities once they actually occur. Given that we now convincingly know from far more than telescopic evidence that the Moon has mountains (e.g., the Apollo 11 landing) and that Jupiter has satellites (e.g., the Galileo orbiter), Galileo's discoveries become incredibly obvious, and those contemporaries who denied his conclusions thus appear unbelievably rigid or even stupid.[3]

It is more important to note that the foregoing distortions of Galileo's astronomy—whether styled as presentist fallacies, Whig histories, or hindsight biases—do not do full justice to the psychological complexities of discovery. His contributions are too often depicted as a succession of pure hits with no misses. Because Galileo was a "genius" with awesome powers of logical reasoning and empirical observation, he alone was able to revolutionize our conceptions of the heavens. However, the psychological truth is far more intricate. The same mind that could exhibit exquisite insights could also commit surprising oversights if not outright blunders. More complicated still, sometimes the very same manner of thinking that supported his greatest triumphs could also induce his most embarrassing failures.

It is my purpose to scrutinize Galileo's astronomical observations with the ultimate aim of illuminating the psychology of scientific discovery. I wish to examine more specifically what his telescopic observations tell us about the interlocking roles of foresight, insight, oversight, and hindsight. In brief, how truly sighted were his sightings? Later, I will briefly investigate Galileo's theories that relate directly to his astronomy. After all, his telescopic observations were often taken as evidence for his theoretical positions, positions that may or may not have been even correct. However, before I can perform the proposed analysis, I first must define the central terms.

Central Terms Defined

I have two definitional tasks. First, I must take four everyday terms and make them somewhat more technical. Second, I must take two technical terms and make them more amenable to the qualitative analysis pursued in this investigation.

Insight, Foresight, Oversight, and Hindsight

In each instance below, I start with dictionary definitions and then make the necessary modifications or elaborations in the key idea.

Insight. The usual definitions of this concept are not very helpful. For example, one standard dictionary defines insight as "The capacity to discern the true nature of a situation; penetration" (*American Heritage Electronic Dictionary*, 1992). Dictionaries more specialized do not do any better, as illustrated by "Mental discernment or apprehension of the true nature of a problem, object, person, or situation" in Wolman's (1989, p. 179) *Dictionary of Behavioral Science*. Neither of these definitions seems that different from what could be used to define mere "perception." Furthermore, researchers who study insight have yet to reach any consensus on their usage (e.g., Sternberg & Davidson, 1995). Hence, it is imperative to specify how the term is used here. My point of departure is the distinction that Perkins (2000) made between reasonable and unreasonable problems. The former "can be reasoned out step by step to home in on the solutions" whereas the latter "do not lend themselves to step-by-step thinking. One has to sneak up on them" (p. 22). Only a solution to the latter can be said to involve true insight and thus evoke an "aha!" or eureka experience.

This contrast closely parallels Amabile's (1996) distinction between algorithmic and heuristic tasks, respectively, except she goes on to say that heuristic tasks are more strongly associated with creativity. She specifically stressed that "a product or response will be judged as creative to the extent that (a) it is both a novel and appropriate, useful, correct or valuable response to the task at hand, and (b) the task is heuristic rather than algorithmic" (p. 33). The connection between creativity and insight is also implicit in Boden's (2004) requirement that a creative idea be novel, valuable, and surprising as well as in the stipulation of the U.S. Patent Office that an invention be new, useful, and nonobvious (see http://www.uspto.gov/inventors/patents.jsp). Notably, "nonobvious" is defined with respect to someone who has "ordinary skill in the art"; that is, someone who has the relevant domain-specific expertise. When an idea results from the obvious application of such expertise, the result is considered reproductive or routine adaptation rather than a productive or creative innovation (cf. Kirton, 1976; Maier, 1931; Weisberg, 1995; Wertheimer, 1945/1982).

Foresight. According to the dictionary definition, foresight entails the "Perception of the significance and nature of events before they have occurred" (*American Heritage Electronic Dictionary*, 1992). Because this perception could be obvious rather than surprising, here I link foresight more directly with insight: Foresight is insight operating in the future tense. This connection results in a distinction between reasonable (algorithmic or routine) predictions and unreasonable (heuristic or insightful) predictions—only the latter being indicative of superior foresight.

[3] The latter ascription was no doubt amplified by Galileo's own rhetorical inclination to subject his opponents to the most scathing ridicule. As an example, in his *Dialogue Concerning the Two Chief World Systems*, Galileo names the Ptolemaic (and Aristotelian) proponent "Simplicio," a likely allusion to the Italian word for "simple," implying that such traditionalists are "simple minded." Although by Papal decree the *Dialogue* was supposed to offer an even-handed presentation of the two world systems, Simplicio seems to get the worse end of practically every argument. It did not help Galileo's case before the Inquisition that he had Simplicio present the Pope's own personal take on the debate between Ptolemaic and Copernican systems.

Oversight. An oversight is commonly defined as "An unintentional omission or mistake" (*American Heritage Electronic Dictionary*, 1992). That is, an oversight occurs when someone overlooks something that should have been seen. Consistent with what was said about insight, it is assumed that what was overlooked should have been obvious at the time, the oversight then evoking retrospective surprise. When T. H. Huxley first learned of Darwin's evolutionary theory he exclaimed "How very stupid not to have thought of that" (Sulloway, 1996, p. 18). Regarding the requisite domain-specific expertise, Huxley already knew what Darwin knew, but he failed to connect the dots. Likewise, many serendipitous discoveries entail events that "were *seen* numbers of times before they were *noticed*" (Mach, 1896, p. 169). Alexander Fleming's discovery of the antibiotic properties of penicillin is a case in point. He was not the first to see the effects of a particular mold on bacteria cultures.

Hindsight. Lastly, hindsight has been not very usefully defined as the "Perception of the significance and nature of events after they have occurred" (*American Heritage Electronic Dictionary*, 1992). I will instead turn to the definition of hindsight bias in *A Dictionary of Psychology*: "The tendency for people who know that a particular event has occurred to overestimate in hindsight the probability with which they would have predicted it in foresight" (Colman, 2001, p. 333). The post hoc reappraisal of the probabilities is reflected in the old saying, "Hindsight is always 20–20." As suggested earlier, one manifestation of this phenomenon is especially important: The retrospective tendency to view discoveries as far more "sighted" than they really were at the time—which brings me to the next set of definitions.

Sightedness and Blindness

More than a half century ago, Campbell (1960) proposed his classic blind-variation and selective-retention (BVSR) theory of creativity (Simonton, 2011b). Simply put, creative ideas are discovered by generating and testing "thought trials" that may or may not prove useful because the creator cannot know beforehand what will prove fruitful without engaging in some trial-and-error procedure. Sternberg (1998) later introduced the term "sighted" to describe the opposing point of view that creative ideas do not require any BVSR. In this contrary position, the application of basic cognitive processes to an acquired domain-specific expertise enables a creator to bypass the supposed need to generate and test alternative solutions or concepts (Weisberg, 2006).

Too often, the debate between "blindness" and "sightedness" is expressed in polarized terms when the two properties are better conceived as labels for the opposite ends of a bipolar continuum (Simonton, 2011a; cf. Kronfeldner, 2010). In fact, it is possible to devise a mathematical measure of variation sightedness that varies from 0 = *totally blind* to 1 = *totally sighted*.[4] One useful consequence of this measure is the formal demonstration of a seeming paradox. On the one hand, highly creative ideas cannot emerge when blindness is absolutely perfect (viz., all ideas considered are useless). On the other hand, highly sighted ideas cannot be highly creative! The resolution of this paradox is that highly creative ideas are most likely to appear at the lower "blind" end of the blind-sighted continuum (Simonton, 2011a). These "nearly blind" ideas have low probabilities but high utilities. Because the formal definition is too technical to be useful in the following analyses, I propose informal definitions that should suffice for the present interpretative purposes.

Sightedness. Sightedness takes place whenever factual- or theory-driven expectations correspond to actual outcomes. In other words, ideas that are the most useful have the highest probabilities and ideas that are the least useful have the lowest probabilities. Indeed, under perfect sightedness, useless ideas would have no likelihood of generation, and if only one useful idea exists, then that one idea would have a probability of unity. Needless to say, the outcomes at this end of the blind-sighted continuum also have zero surprise. There is also no need whatsoever for a generate-and-test procedure to weed out the good ideas from the bad ideas because there are no bad ideas in the first place!

Blindness. Some degree of blindness occurs when ideational probabilities are not highly correlated with their corresponding utilities (Simonton, 2011a, 2011b). This lack of correlation manifests itself two principal ways. First, the probabilities of certain ideas may be roughly equal although the usefulness of those ideas may be very unequal (viz., only one idea in the set of ideas actually works). An example would be two alternative explanations for a phenomenon that are equally likely on theoretical grounds although only one can be empirically correct. Second, the probabilities and the utilities may be inversely related; that is, the idea with the highest probability of generation has the lowest utility and the idea with the lowest probability has the highest utility. Because the most creative ideas have the lowest probabilities but the highest utilities, this second scenario implies that "the best is saved for last" (see, e.g., Derks & Hervas, 1988; Parnes, 1961). In any case, blindness increases with the number of thought trials—or what has been called "variant superfluity" (Simonton, 2011b).

Given the hindsight bias, notice that an idea with a low probability but a high utility eventually becomes a high-utility idea with a high probability, thereby converting it from a largely blind idea to a seemingly sighted idea. This retrospective reassessment renders BVSR far less conspicuous even when it had a prominent role at the time.

Galileo's Telescopes

Below I review Galileo's principal telescopic inventions and discoveries. Although this review relies on many sources—primary (Galilei, 1638/1952, 1632/1953, 1623/1960, 1610–1638/2008) and secondary (Drake, 1978; Heilbron, 2010; Wooton, 2010)—the single most important source is Van Helden's, 1989 translation of Galileo's 1610 *Siderus Nuncius or The Sidereal Messenger* along with the translator's elaborate and scholarly

[4] More formally, given a set of k ideas (e.g., alternative telescope lenses and their configurations), where $k \geq 1$, we can define the sightedness metric $S = 1/k\ \Sigma\ p_i u_i$, where p_i is the probability of the ith idea in the set (and where $\Sigma\ p_i = 1$) and u_i is the idea's respective utility value (e.g., proportion of usefulness criteria satisfied, where $0 \leq u_i \leq 1$). Because it necessarily follows that $0 \leq S \leq 1$, the set's blindness is defined as $B = 1 - S$. This blind-sighted metric circumvents unnecessary either-or debates about BVSR (cf. Simonton, 2011a, who uses different definitions and metrics). Nevertheless, if creative ideas are defined as those having very low probabilities but very high utilities, then it follows mathematically that such ideas are more likely to appear as $S \rightarrow 0$ (i.e., the latter results whenever $p_i \rightarrow 0$ as $u_i \rightarrow 1$).

introduction, conclusion, and notes to the text. It was in *The Sidereal Messenger* where Galileo reported his first astronomical observations. Also of use were various Internet websites, such as Van Helden's (2003) own Galileo Project, which provides background information, and the website What Galileo Saw (Pope & Mosher, 2009), which posts direct comparisons between Galileo's drawings and photographs taken with a faithful reconstruction of his telescope.[5]

I have deliberately concentrated on those biographical and historical facts about which there is no debate. In particular, because Galileo seldom dated the pages in his notebooks and manuscripts, scholars sometimes disagree regarding the precise dates that Galileo made certain telescopic observations (Drake, 1976). Even so, the same scholars will concur that his recorded observations—and the corresponding inferences—were in fact made. Given that my ultimate goal is psychological, the latter consensus provides sufficient basis for my conclusions regarding the process of scientific discovery. His notebooks, manuscripts, and publications suffice to reveal his thought processes (see also Gruber, 1974). With that in mind, below I treat the two categories of Galilean contributions to observational astronomy: instrumental inventions and empirical observations.

Inventions

Although the instrument that Galileo used is now eponymically referred to as a "Galilean telescope," he did not actually invent the instrument. That achievement belongs to the Dutch, albeit it is difficult to identify the actual inventor. Its advent may constitute a bona fide instance of a "multiple" discovery in which two or more persons independently arrive at the same creative idea (Merton, 1961; Ogburn & Thomas, 1922; Simonton, 1979; for a probabilistic explanation, see Simonton, 2010). What can be determined with confidence is that in 1608, Hans Lippershey, a German-Dutch spectacle maker, unsuccessfully requested a patent for a "spyglass" in the Hague. A little earlier, the instrument had been pointed at the stars, but no major astronomical discoveries were reported. However, in May of the following year, Galileo first learned of the new invention, and within a month's time, he had duplicated the device in the form of a three-powered telescope. Galileo used spectacle lenses that were readily available from the local "optometrist" shops of his day. He merely had to find, via tedious trial and error, the right combination for the objective and ocular lenses. Because he did not know the optimal configuration, this search was mostly but not entirely blind.

If Galileo had been content to inspect the night sky with this instrument, his discoveries would have been minimal. For example, the distinguished English mathematician and astronomer Thomas Harriot only about a month later (and unknown to Galileo) had made drawings of the Moon using a six-powered telescope, but he did not reveal any features substantially beyond what could be achieved with the naked eye—certainly no discovery that can be considered a "breakthrough." If otherwise, then Harriot might have made Murray's (2003) list of the 767 most significant astronomers in history. Instead, Galileo realized that he would have to invent telescopes with substantially higher magnifications. In hindsight, that realization was an important insight, but the implementation of that insight was far from sighted. As a mathematician and physicist, Galileo was certainly not ignorant of the prevailing optics of his day (an academic subject that he taught privately in 1601 at Padua; Drake, 1978). However, whatever knowledge he might have possessed would have had no utility in the present case. Contemporary optics did not then deal with such two-lens systems. Moreover, it soon became clear that telescopic power had attained a maximum using ready-made spectacle lenses. Consequently, he had no other option but to (a) learn how to personally grind lenses more powerful than what was available "off the shelf" and (b) identify the optimal lens combinations using rather substantial "trial and error," "generate and test," or, more simply, BVSR (Campbell, 1960; Simonton, 2011a, 2011b). In line with the informal definition of blindness given earlier, what was not known a priori had to be determined a posteriori: Galileo had to laboriously produce multiple prototypes that may or may not work and even less improve upon the instruments he already made. The optimal configuration was by no means obvious.

Even then, Galileo apparently never understood how his telescope actually operated because the drawing provided in the 1610 *Sidereal Messenger* showed that the rays refracted at the objective lens but not at the eyepiece, rendering the latter lens seemingly superfluous (see Galilei, 1610/1989, p. 39). However, as Kepler was able to show only a year later, the latter lens has critical repercussions regarding the field of view and the inversion of the image (Van Helden, 1989; Wooton, 2010). Worse still, Galileo continued to use his instrument long after it became obsolete, not realizing that certain observational techniques are best performed with Kepler's design (still the preferred form for two-lens refracting telescopes). Galileo may not have even understood Kepler's new optics justifying his original invention (Wooton, 2010). Galileo's "blind faith" in his observations was very weakly grounded—insight was absent.

Galileo eventually devised a telescope that multiplied eight or nine times, therefore he presented his higher-powered telescope to the Senate of the Venetian Republic in the hope of gaining some material advantage. In those early years, the instrument was highly appreciated for its potential military utility. Especially for a maritime power such as Venice (and the Netherlands), it was most advantageous to obtain advanced warning of enemy forces on the sea's horizon. Although Galileo's salary was doubled, and he obtained lifelong tenure at his university, the rewards fell short of expectations, motivating him to improve the instrument still further. In the last two months of 1609, he had arrived at a 20-powered telescope. With this instrument, he began making lunar observations that he recorded in a series of eight or more drawings. Relatively minor modifications to this telescope proved capable of making the observational discoveries that made Galileo famous throughout Europe.

The invention of Galileo's telescope leads to two additional points. First, because intrinsic motivation is considered more conducive to the free exploration of a heuristic task—which would facilitate the discovery of low-probability but high-utility ideas—creativity is often viewed as intrinsically rather than extrinsically motivated (Amabile, 1996). Even so, the extra effect of extrinsic motivation cannot be denied in Galileo's case. For reasons that we need not delve into (including his mistress and their illegitimate

[5] Purported replicates of Galileo's telescope can now be ordered by mail or Internet for the curious who want to see for themselves what he saw.

children), his domestic finances were often somewhat precarious and his current university position could not completely remedy the situation (nor was it likely to change given that he was a college dropout sans degree). Galileo clearly viewed the telescope as a venture that might allow him to improve his material circumstances (just like the substantial money he made from his Swiss-Army-knife-like sector or "compass"; see Wooton, 2010, Plate 4). Even when Galileo switched from making military instruments to conducting astronomical observations, that original goal remained. This motivation is vividly depicted in Bertold Brecht's (1952/1966) classic play *Galileo*, in which the title character denies that he is a scientific hero and instead claims that he always acted out of self-interest. This latter drive may even have led Galileo to be somewhat more competitive, secretive, and combative than is consistent with the mythological image of the disinterested "truth seeker" (cf. Koestler, 1959). He claimed his intellectual territory with considerable assertiveness while at the same time being most unwilling to acknowledge the intellectual property of his competitors. In this respect, Galileo manifested the "hostility" and "arrogant working style" that Feist (1993) found to characterize high-impact natural scientists at top-notch research universities.

Second, although Galileo's early telescopes were noticeably superior to any instrument produced by his contemporaries anywhere in Europe, the invention remained vastly inferior to what can now be bought cheaply at any toy store. The inferiority had multiple causes. For one thing, the basic design meant that the instrument had a very small field of view in comparison to alternative designs (e.g., the Keplerian telescope conceived only 2 years later). To provide a concrete illustration, his telescope could only reveal somewhere between one half and one quarter of the Moon's surface at one time. Seeing the whole Moon was impossible. This restriction was so severe that a 30-powered telescope may not have provided a genuine improvement over a 20-powered instrument. Rendering matters even worse, because Galileo followed the traditional practice in grinding his lenses to represent segments of spheres, his instruments suffered from severe spherical aberration (unlike the hyperbolic-shaped lenses soon recommended by Kepler; Van Helden, 1989). These and other problems obliged Galileo to introduce makeshift adaptations in his instruments (e.g., stops to narrow the apertures) and to provide specific instructions in their use (e.g., to overcome the difficulty that the image seen was highly contingent on the exact position of the eye relative to the eyepiece). These precautions would be required to ensure that other viewers could replicate his observations. It would be difficult for an uninstructed observer to see what Galileo claimed to observe by simply pointing his telescope toward the appropriate object in the night sky. Indeed, some who tried to do so failed to confirm his observations even when using telescopes that he had handmade. His sightings were certainly unobvious!

Observations

Once Galileo obtained an instrument that could discern celestial objects with a resolution unobtainable by any other scientist, he began his somewhat unsystematic survey of the skies. It is critical to recognize that he had no idea what he would actually see, but he just blindly hoped that he would find something interesting. Magnifying a celestial object 20 times could possibly reveal new discoveries, but there was no guarantee. On the contrary, the prevailing Aristotelian cosmology and Ptolemaic astronomy of his day would rather firmly predict that he should find absolutely nothing worthy of note. The a priori expectation was nil. In terms of classic BVSR theory, pointing an unproven optical instrument toward the night sky just to see what might be there was about as close to blindness as can occur in science. For that reason, many of his observations proved useless. In any event, during his observational career, Galileo made fundamental discoveries regarding the Moon, planets, stars, and the Sun.

Moon. The first object of his attention was the Earth's moon, a celestial object second only to the Sun in apparent size (Galilei, 1610/1989). What he eventually (but not immediately) discovered was a very big surprise: the Moon's mountains. This discovery flatly contradicted the Aristotelian cosmology that established an emphatic dichotomy between the terrestrial and celestial worlds (Aristotle, c. 350–c.320 BCE/1952). The objects in the latter domain should consist of perfect spheres. However, it was evident that the surface was very uneven because the line between the dark and light side of the Moon took the striking form of an irregular zigzag. He also spotted a large crater that he compared to what would be seen on Earth if we looked down on the plain of Bohemia at dusk or dawn. It is interesting to note that although Galileo's drawings make a strong case for his main inference, they are not precise enough to identify the specific lunar features that he observed. These discrepancies presumably would not have facilitated attempts at replication by independent conscientious observers.

Although in hindsight we know that Galileo drew the right conclusion, it is essential to note that the available data did not then completely support his interpretation. If the Moon had such rough topography, then the edge of the Moon should not appear as a perfectly smooth circle. Rather, the outer circumference should also be jagged. However, that was manifestly not the case! This critical discrepancy between observation and interpretation Galileo explained two ways—both of which exhibited zero insight! The first post hoc explanation was that the peaks and valleys would cancel out when we look toward the edge of the lunar disk, and the second was that the Moon was covered in some vapor that obscured the roughness of the outer edge (albeit this second interpretation was dropped approximately 20 years later; Galilei, 1632/1953). It turns out that the true explanation is one that Galileo would very likely not want to admit even if he had conjured up the idea himself (and perhaps did so but kept silent): His deficient telescope did not have sufficient magnifying power to make the necessary resolution. Nowadays we can make out the Moon's ragged circumference. However, if he had professed that his telescope was not good enough to make out the mountains in that case then that would undermine the main inference. He could not have it both ways.

A key question in this central episode is why Galileo was able to spot what was not obvious to others, even after he published his interpretation. It is too simplistic to say that Galileo enjoyed some special "domain-specific expertise" conferred on him from his unique position as a pioneer in telescopic observations. This interpretation is contaminated with substantial Whiggish hindsight bias because that narrow expertise did not yet exist. Nobody, not even Galileo, knew how the telescope actually worked at the time the observations were made! The secret to his telescopic success lies elsewhere—and in an unforeseen place. But before I get to that revelation, let me first review the relevant findings from psychological research.

One of the recurrent debates in the literature is the degree to which creativity is a domain-specific expertise rather than a generic capacity (Baer, 2011; Simonton, 2009). In support of the former hypothesis is the so-called "10-year rule" that states that creators must devote a full decade to domain-specific "deliberate practice" before they can expect to make world-class contributions to that domain (Ericsson, 1996; Hayes, 1989). Moreover, it is supposed that the more such expertise is acquired—the more knowledge and skill—the greater must be the resulting creativity (cf. Kaufman & Kaufman, 2007; Simonton, 2000). The greatest creators are the greatest experts. However, very little evidence supports this view (see also Campitelli & Gobet, 2011). Highly creative individuals tend to score high on openness to experience (Carson, Peterson, & Higgins, 2005; Harris, 2004; McCrae, 1987), to have wide rather than narrow interests (Gough, 1979; Root-Bernstein et al., 2008; Root-Bernstein, Bernstein, & Garnier, 1995), and to be highly versatile (Cassandro, 1998; Cassandro & Simonton, 2010; Simonton, 1976; Sulloway, 1996; White, 1931). Such creative geniuses do not seem to be monomaniacs who drudge away at refining some increasingly narrow competence (but see Feist, 1997, and Simonton, 1992, for complications). This breadth of curiosity and ability then bears fruit in unexpected ways, permitting the creator to "think outside the box" that otherwise would be imposed by unadulterated expertise (see also Frensch & Sternberg, 1989).

Galileo provides an exemplar of this second viewpoint. Galileo was the son of a notable Florentine musician and music theorist with whom he may have conducted some pioneering experiments as a youth (Drake, 1978). Galileo also took great interest in the visual and literary arts (Heilbron, 2010). Having artists as friends (most notably the Florentine painter Lodovico Cigoli), Galileo developed some skill at drawing—as witnessed in his graphic representations of the lunar mountains—and was a frequent literary critic. With somewhat less success, he even tried his hand at creative writing, albeit most of his scientific works are considered masterpieces in Italian literary prose, a brilliance that is not completely lost in translation. These artistic engagements gave him an instant advantage over any contemporary, such as Harriot, who might also point their own telescope toward the Moon.

Galileo's artistic training in the representative technique of chiaroscuro had special relevance (Edgerton, 1991, chap. 7). He alone was able to appreciate the implications of the dark and light regions, regions that indicated not only the shadows cast by the mountains but (also) the mountain peaks high enough to catch the solar rays after darkness had settled in the valleys (cf. "alpine glow"). It is instructive to compare Harriot's lunar drawings made before and after he heard of Galileo's discovery (see, e.g., Heilbron, 2010, p. 151, Figure 5.1). Harriot's earlier drawings show no hint of relief, whereas the later drawings capture the existence of major topographical features. Galileo's advantage over Harriot was not that he had superior domain-specific expertise because the field of telescopic astronomy was brand new, sans any expertise to be had. Instead, Galileo, Harriot, and other contemporaries were then actively creating that expertise from scratch. Galileo's observational superiority came from a source that had no a priori connection with either optics or astronomy—namely, painting and drawing. This scientifically esoteric knowledge allowed Galileo insights that were unsighted in the sense that the insights could not possibly have been foreseen by any contemporary expert.[6]

Once Galileo invented lunar astronomy, he could advance to make other discoveries about the Moon. Late in 1637 and already blind in his right eye, Galileo reported a new lunar libration (there are three altogether). By the beginning of 1638 he also became totally blind in his left eye, and his astronomical observations ceased, but not before he had added the discoveries that follow.

Planets. In the Ptolemaic system, the planets all rotate around the Earth just like the Earth's moon (even if with some complicating epicycles to account for retrogressive motions). Hence, it would seem a natural next step for Galileo to direct his telescope toward the known planets. Unfortunately, many of the then-known planets were not in the optimal orbital positions for telescopic observations. Venus was then in the morning sky, and Mars and Saturn were too close to the Sun and the most distant from the Earth. Only Jupiter was in ideal position: It was relatively close to the Earth (and moving in retrograde relative to the so-called "fixed stars"). For this somewhat arbitrary reason, it was Galileo's observations of Jupiter that not only brought him immediate fame but (also) the most lucrative monetary rewards. Only later was he able to make telescopic observations with respect to other planets, observations that had varying degrees of success. Below I concentrate on Jupiter, Venus, and Saturn.

1. *Jupiter's moons*—When on January 7, 1610, Galileo pointed an improved telescope ("superlative instrument") toward Jupiter, he saw something never seen before ("because of the weakness of the other instruments"; Galilei, 1610/1989, p. 64). In particular, Galileo noticed three little stars that he first took to be fixed stars that formed part of the cosmic backdrop in Ptolemaic astronomy. However, these bright lights intrigued him because "they appeared exactly along a straight line and parallel to the elliptic, and to be brighter than others of equal size" (Galilei, 1610/1989, p. 64). Weather permitting (because some nights were cloudy), Galileo was able to infer that Jupiter had four satellites orbiting around the planet. Because the Earth was not considered a planet in the Ptolemaic system, this was the first time that any planet was shown to have what we now call moons. Galileo at once realized the importance of his discovery and decided to name the four moons the "Medicean stars" to honor his prospective patron, Cosimo II, Grand Duke of Tuscany, to whom *The Sidereal Messenger* was dedicated. Galileo was handsomely rewarded with a lucrative and lifetime position as the Ducal "Mathematician and Philosopher" along with a professorship at Pisa that had no teaching responsibilities. His extrinsic motives had been more or less satisfied.

[6] Galileo the literary critic had a special affection for Ludovico Ariosto's poem *Orlando Furioso* (Heilbron, 2010). This work includes a key scene that takes place on a rather Earth-like moon. Although pure fiction, one wonders whether this image had some effect on Galileo's later telescopic observations of the lunar surface. If so, this would constitute another example of where extraneous artistic interests can contribute to scientific discovery. It should be emphasized that this type of contribution is distinct from the direct involvement of aesthetic judgments in scientific work, such as assessments of mathematical elegance or equation "beauty" (e.g., Dirac, 1963). The latter evaluations remain within a given scientific discipline rather than entail the transfer of artistic knowledge, skill, or interests to a scientific discipline (for further discussion, see McAllister, 1991; Osborne, 1984).

It took some time for this discovery to receive empirical vindication by other scientists (Van Helden, 1989). Only a few telescopes available during this period were capable of making the necessary observations. Furthermore, not all four moons would always be viewable. For example, whenever a moon was too close to Jupiter it would be obscured by the planet's glare. A moon might also occasionally be outside of the field of view. Nonetheless, in time Kepler and other astronomers were able to confirm Galileo's discovery. The theoretical implications were enormous. A principal criticism of the Copernican system was that the Earth became the only planet with a moon, whereas in the Ptolemaic system the Moon was just one of several celestial objects, including the Sun, which rotated around the Earth. However, now that Jupiter had moons, the Earth would be no longer unique.

Some years later Galileo published the periods for all four of Jupiter's moons. Many years after that determination, he proposed to the Dutch States General a scheme for calculating longitude at sea by observing the eclipses of those same satellites (Van Helden, 1989). A practical solution to this critical navigational problem would earn a substantial monetary prize. Although the States General awarded his efforts with an expensive gold chain (which he was obliged by the Inquisition to refuse), his proposed method was deemed unworkable. In Popper's (1963) BVSR-like terms, the idea represents a definite "conjecture" and "refutation." Even so, Galileo continued to expend futile effort on the technique, devising elaborate technological devices that only betrayed his utter ignorance of the pragmatics of taking extremely precise astronomical measurements from a ship sailing across open oceans. Galileo evidently never took a long sea voyage in his entire life, so his inventions displayed no insight whatsoever into the difficulties involved. The general method was still posthumously proven useful for determining longitudes when confined to land-based observations.

In retrospect, yet another failure was even more remarkable: Between 1610 and 1613, Galileo's observations of the Jovian moons include three to four sightings of Neptune, a planet not officially discovered until 234 years later (Standish & Nobili, 1997). The eighth planet is actually included in his sketches and its location noted relative to Jupiter and its satellites. Although Neptune, like the Jupiter system, was moving relative to the fixed stars, the astronomer completely failed to notice that fact and thus also considered it a fixed star. If Galileo had drawn the correct inference from his own drawings, Neptune (and not Uranus discovered in 1781) would have been the first new planet since antiquity. This failure must count as a substantial oversight: Galileo was quite blind to something not just before his very eyes, but an object that he himself had carefully put down in his very own notebooks.

2. *Venus's phases*—With respect to the debate between the Ptolemaic and Copernican planetary systems, Venus had a very different status than Jupiter. Where Jupiter's moons removed one objection against the Copernican system, Venus had the potential of providing a critical empirical test between the two main rival hypotheses (omitting from consideration the compromise Tychonian hypothesis). The critical test resulted from the fact that only in the Copernican model would Venus exhibit the full set of phases just like the Earth's moon does (Van Helden, 1989; see also Palmieri, 2001). Although this prediction was clear cut, its confirmation required that Venus be in the right position relative to the Sun and Earth and that Galileo have a telescope up to the task (because the combination of the planet's brightness and the instrument's chromatic aberration would produce a very diffuse image surrounded by fringes of color). By the end of 1610, Galileo was able to conduct the requisite observations, and the results supported the heliocentric over the geocentric prediction. In addition, the immense change in the apparent size of the planet—from the very large crescent to the very small full disk—lent further support to Copernican theory because it was exceptionally difficult to explain such size changes if Venus were to have a circular orbit around the Earth rather than the Sun.

Galileo's drawings of the planet's phases curiously exhibit one unexplained quirk: a definite raggedness along the shadow terminator not unlike that found for the Earth's moon (Galilei, 1623/1960, p. 324, Figure 22). In contrast, the disk itself was drawn with a smooth edge. Was he suggesting that Venus also had mountains? Given that the planet's surface is permanently obscured by a thick atmosphere, it was impossible that he actually saw what he drew. Did theory supersede the data? Was he just covering his bets or just careless? Certainly no insight was operating here.

3. *Saturn's rings*—When Galileo pointed his telescope at Saturn, he made a discovery that made absolutely no sense: Unlike the other planets, Saturn did not appear to be a round disk, but rather it assumed a roughly oval shape, like a circle with two rings on either side (see Galilei, 1623/1960, p. 324, Figure 22). Galileo's observations here were unmistakably pushing the limit of what he could discern using his primitive instrument. Furthermore, he could not immediately comprehend why the protuberances that appeared in 1610 vanished in 1612 only to reappear in 1613. Although he was eventually able to predict the regularity of their appearances and disappearances, it was not until more than a decade after Galileo's death that astronomers determined what he actually saw: the rings that surround the planet—rings that will periodically vanish with respect to the Earth as Saturn orbits around the Sun. This planetary feature is sometimes viewed edge-on and thereby the rings become invisible (Van Helden, 1974).

Because the Venus and Saturn observations occurred after the publication of *The Sidereal Messenger*—which he got out in a big slap-dash rush to obtain "fame and fortune"—Galileo needed to claim priority until his next publication (scientific journals were still far in the future). Therefore his discoveries were first revealed in two cryptic Latin anagrams—one revealing that Venus had phases similar to the Moon and the other that Saturn was "triform" (Van Helden, 1989).

The only other planets known at the time were Mars and Mercury. Although Galileo apparently only observed the former, his best instruments proved too inadequate to reveal anything significant—a clear "blind variation" inasmuch as by that point he might have thought to have found at least something interesting! Instead, he just verified that Mars displayed the expected disk (Galilei, 1623/1960, p. 324, Figure 22). The planetary disk contrasts with the stars, which, we now know, only get brighter with increased magnification. Thus, it is to the stars that I now turn.

Stars. Using his telescope, new stars could be seen that cannot be singled out with the naked eye, inspiring Galileo to conduct a limited survey of the skies and creating entirely new star charts (Galilei, 1610/1989). In *The Sidereal Messenger*, he provides maps of the stars making up the constellations of Pleiades and Orion (belt and sword region), revealing many more stars than were known to antiquity. Even more striking, Galileo showed that the Milky Way consisted of "nothing else than a congeries of innumerable stars distributed in clusters" (p. 62), a fact hitherto unknown. He similarly demonstrated that several so-called "nebulous" stars—such as the nebula of Orion and that of Praesepe—are nothing but "swarms of small stars placed exceedingly closely together" (p. 62).

These new observations are hard to criticize in negative hindsight. Their principal fault is that Galileo could not accurately represent the spatial configurations of large constellations because of his telescope's narrow field of view. These observations were purely data-driven. Later, when Galileo's stargazing became more theory-driven, his powers of observation would sometimes become compromised (e.g., trying to use the double star Mizar to prove that the Earth moves; Pope & Mosher, 2009; cf. Galilei, 1632/1953). Furthermore, his later debate with Jesuit astronomers revealed that Galileo never really understood how his telescope worked at any time during his career. Galileo wrongly believed that the telescope made the stars bigger, as in the case of the planets and Moon, whereas his opponents quite correctly pointed out that the telescope, via its objective lens, only made the stars brighter (because the lens focused more light on the retina). Even today's state-of-the-art optical telescopes cannot see stellar disks—except, of course, for our own Sun, which can be seen with the unaided or naked eye.

Sun. Galileo was not the first to notice the existence of sunspots. Harriot had made sunspot records in late 1610, and in 1611 sunspots were observed by Johannes and David Fabricius and by Christoph Scheiner (here ignoring what Chinese astronomers had recorded many centuries earlier). In short, it was yet another example of a multiple discovery (Simonton, 2004). Nonetheless, unlike the others, especially Scheiner, Galileo was willing to draw far-reaching implications from his solar observations. Where Scheiner first argued that the spots were actually satellites swarming around the Sun—a somewhat ironic expertise-driven extrapolation from the Jovian satellites that once had been so adamantly protested—Galileo insightfully inferred that the spots were actually on the Sun's surface and thereby provided additional evidence against the terrestrial/celestial distinction in Aristotelian cosmology (Van Helden, 1989). Just as the Moon had a rough surface, so the Sun had its own imperfections. The rotation of sunspots also indicated that the Sun rotated on its axis, an axis that was also, similar to the Earth's, off kilter. Imperfections compounded! Galileo's insights here were profound.

Observational astronomy was developing very quickly as a domain, obliging Galileo to confront increasingly more competition from other astronomers. The results were unpleasant priority disputes that alienated many potential allies who might have been more helpful when he faced the Inquisition many years later. His irksome theoretical oversights also did not help.

Galileo's Theories

In addition to instrumental inventions and empirical observations, Galileo would offer theoretical interpretations of astronomical phenomena (particularly later in his life, when his telescopic heyday was over). Of these interpretations, his theoretical views of comets, orbits, and tides are most relevant to the substantive issues driving this article.

Comets

Toward the end of 1618, three different comets appeared in the skies. In response, Orazio Grassi (1619/1960), a Jesuit mathematical astronomer, argued on scientific grounds that the comets were located beyond the Moon (i.e., superlunary) and thus provided additional evidence against the Aristotelian cosmology. The universe beyond the Moon was not eternal and unchanging. One might think that Galileo would have enthusiastically endorsed Grazzi's interpretation, but his response was quite the contrary with Galileo proclaiming that the comets were sublunary optical illusions comparable to rainbows! The resulting controversy ultimately led to the publication of Galileo's (1923/1960) famed *The Assayer*, a powerful and prophetic polemic on behalf of the mathematical analysis of natural phenomena. This work was so brilliant that Galileo was widely thought to have won the debate. However, the fact remains that Grazzi was clearly right and Galileo was plain wrong about the nature of comets. Galileo had apparently developed an antipathy toward the Jesuit astronomers so strong that he could no more tolerate Grassi's contributions to the understanding of comets than he could accept Scheiner's earlier contributions to the understanding of sunspots. He had utterly lost his scientific objectivity, generating ideas for which the probabilities were perforce unassociated with their utilities. Again, the irony here is that Galileo's first telescopic observations, less than a decade earlier, had to overcome a similar objection that the images he had viewed through the eyepiece were mere optical illusions. Why could he not see his blindness?

Orbits

It now has become established fact that comets also orbit the Sun and do so in highly elliptical orbits. For this reason, the major comets return at regular even if lengthy intervals, as Edmund Halley first demonstrated for the comet named after him. Halley's close colleague, Isaac Newton, provided a physical explanation—the universal law of gravitation—for the elliptical orbits of not just the comets but also the planets. Newton's monumental achievement managed to integrate Kepler's three laws of planetary motion with Galileo's new mechanics (with some Cartesian improvements). Galileo (1638/1952) had established that a projectile, such as a cannon ball, would follow a parabolic path resulting from two combined forces—one the inertial force imparted by the initial propulsion and the other the downward and accelerating force exerted by the Earth. In Newton's integration, the elliptic orbits of the planets and the parabolic trajectories of missiles were manifestations of the same underlying inertial and gravitational principles. Indeed, according to Newton's synthesis, if a projectile were thrust with sufficient force at an oblique angle, it would enter into an elliptical orbit rather than return to Earth—an implication confirmed every time the Earth acquires yet another artificial satellite.

Because Galileo died the same year that Newton was born, he never lived to see the magnificent integration that could be considered an exemplar of the very argument Galileo (1623/1960) had presented in *The Assayer*. At the same time, it was a synthesis that

Galileo could not possibly have created himself. Among other obstacles, such as a lesser mathematical competence, Galileo never accepted Kepler's assertion that the planets had elliptical orbits—what is now called the First Law of Planetary Motion. Instead, Galileo insisted, similar to Aristotle before him, that circular motion was the natural course for the heavenly bodies. He maintained this remarkably conservative position despite having over 3 decades to assimilate Kepler's empirical discovery. Galileo's persistence even continued after discovering the new lunar libration that was a direct consequence of the Moon's noncircular orbit (Wooton, 2010).

To be sure, all extant cosmologies, whether Ptolemaic, Copernican, or Tychonian, maintained that the planets had circular orbits. However, it must be considered a major oversight that he did not view Kepler's elliptical orbits as cut from the same cloth as his own parabolic trajectories. After all, ellipses, parabolas, and circles (as well as hyperbolas) all belong to the conic sections that were studied back in antiquity. One can only speculate whether Galileo's continued use of spherical rather than hyperbolic lenses in his telescopes constituted yet another manifestation of this procircle cognitive bias. In any case, he had a definite blind spot for ellipses.

However, in fairness, Galileo was simultaneously engaged in overthrowing two potent traditions. On the one hand, he became a staunch advocate of the Copernican over the Ptolemaic world system. For this advocacy, circular orbits were all that were required. Moreover, Galileo did not have to create the new astronomy from scratch but instead could content himself with testing the heliocentric implications and demonstrations (e.g., the phases of Venus). On the other hand, Galileo devoted far more of his career to developing a mechanics (physics) to replace what European civilization had inherited from Aristotle. This second goal was much more difficult given that Galileo pretty much had to start from ground zero. Each time he had refuted some ancient, Aristotelian principle—such as the notion that heavy objects fall faster than light objects—it became incumbent upon Galileo to create the alternative, more modern physics. In truth, the BVSR-type "conjecture and refutation" was far more prominent in Galileo's physics than it was in his astronomy (cf. Heilbron, 2010). Even by the time he published *Dialogues Concerning the Two New Sciences* just a few years before his death, he still left many crucial issues unresolved—resolutions that were left to René Descartes and Isaac Newton.

In any event, insofar as Ptolemaic astronomy was reinforced by Aristotelian physics, these two iconoclastic goals could often be complementary. For example, according to the Aristotelian-Ptolemaic conception, the Earth was the center of the cosmos because it was made of the heaviest elements, whereas the heavenly bodies had a far more ethereal composition. So if heavenly bodies were shown to be of the same substance as the Earth—with their very own irregularities and defects—then this mutual support was demolished. However, sometimes these goals operated at cross-purposes, a dilemma seen in the next section.

Tides

The very last part ("The Fourth Day") of Galileo's (1632/1953) epochal *Dialogue Concerning the Two Chief World Systems* presents his theory of the tides—of why sea levels exhibit their periodic rise and fall. Moreover, his theory had a definite purpose: It was his primary proof that the Earth moved! In essence, the Earth's twofold movement—rotation on its axis and its orbit around the Sun—caused the water in the ocean basins to "slosh" back and forth. The mechanism would be somewhat analogous to what happens when a person carrying a cup of coffee causes the liquid to spill over the cup's edge because of the rocking motion associated with walking. The spilling would "prove" the walking. It admittedly would be an act of Whig history to criticize Galileo's theory for not evoking the gravitational effects the Moon and Sun exerted on a rotating Earth. That said, Galileo's theoretical explanation was not even adequate on its own terms. There are two main reasons for this inadequacy.

First, his theory could not explain the nitty-gritty details of the phenomenon, such as the occurrence of two high tides a day or the systematic but complex regularities in the relative magnitudes of the tidal ebb and flow. Galileo's tidal theory also deliberately ignored the very apparent connection between the tides and the Moon, a link essential to Kepler's contemporary explanation (and which is an integral part of the modern account).

Second, and more fundamentally, his tidal theory appears to contradict a core premise of his pro-Copernican argument. A crucial objection to the heliocentric system is that it is inconsistent with everyday personal experience. If the Earth were rotating on its axis to create day and night, then the Earth's motion at the equator would exceed 1,000 mph, and the Earth's velocity in orbiting around the Sun would be far, far faster still. However, nobody feels or notices any movement at all. Why do clouds still trace their leisurely pace across the sky? Why are birds not swept away? To address this question, Galileo quite insightfully evoked the concept of inertia—all objects on Earth are imparted with the Earth's same motion. If a cannon ball were shot straight up, it would still land back in the cannon's mouth; if a weight were dropped from the top of the mast of a moving ship, it would land at the very base of the mast. Hence, the Earth's rotational and orbital motion is undetectable. Then, Galileo decides to contradict himself by introducing an odd exception: the back-and-forth jerking of the seas. Although this hypothesized effect could certainly be detected empirically, Galileo did not attempt to do so, nor did he even deem it necessary. The tides very existence were simply taken as direct and conclusive proof that the Earth moved.[7]

The psychology of science has often dealt with the potential effect of confirmation bias on scientific discovery (e.g., Mynatt, Doherty, & Tweney, 1978; for review, see Nickerson, 1998). In line with Popper's (1959) falsification doctrine, it is presumed that science does not progress if its practitioners are too motivated toward confirming their cherished hypotheses (but see Mitroff,

[7] Galileo was a master experimental scientist who often strove to measure effects or phenomena far more difficult that required for testing his tidal theory. A case in point is his unsuccessful attempt to measure the speed of light, a feat not accomplished until nearly a quarter century after his death, and then, ironically, using one of Jupiter's moons to make an indirect estimate—a direct estimate not succeeding until 2 centuries after Galileo's death! Equally ironic is the fact that when the Earth's movement was finally proved using a terrestrial experiment, the proof relied on the pendulum, a phenomenon that Galileo had studied early in his career but never saw as connected to the Copernican controversy. In hindsight, this is yet another potential oversight.

1974). That behavioral scientists appear more likely to confirm their conjectures than holds for natural scientists cannot be taken as special credit to the former relative to the latter (Fanelli, 2010). Even so, Galileo's confirmation bias in the case of his tidal theory could not be stronger. His desire to render the Copernican astronomy victorious far exceeded his aspiration to establish a coherent post-Aristotelian physics. Worse still, he had been explicitly warned by the Pope himself not to pursue this argument. Galileo's intransigence on this point hammered the final nail on the coffin being prepared for him by his enemies in their arguments before the Inquisition. He was as naive to the potential consequences of his persistence as he was to the scientific absurdity of his position—which together amount to a "tragic flaw" worthy of the protagonist in an ancient Athenian drama.

Conclusion

In this article, I have used Galileo's hits and misses in astronomy to enhance the appreciation of scientific discovery. It should be apparent by now that this phenomenon is far more complex and uncertain than first meets the eye. Galileo could not possibly foresee the consequences of pointing his crude telescope toward the night sky, nor did he have sufficient insight into his instrument to know for sure what he saw—or to avoid overlooking what he should have seen. Moreover, these intricacies are often obscured by the retrospective biases that we impose on the historical record. Whenever Galileo was right by modern standards, his achievements are acclaimed, but whenever he was wrong, his errors tend to be ignored. Galileo strongly believed that his tidal theory was one of his signal contributions to science—one he was willing to take great personal and professional risks to promulgate—yet how many readers of this article were previously aware of this catastrophically wrong-headed idea? Most of us are far more cognizant of his "successes" than his "failures." Even so, from a purely psychological standpoint, it was precisely the same intellect responsible for both outcomes. The same mind that could record Jupiter's satellites could also ignore a new planet jotted down right next to those very moons. The same person who could discern the lunar mountains could also maintain that the comets were sublunary illusions. The same scientist who was so open to the potentials of a new physics and astronomy could often be blind to the comparable discoveries of his contemporaries.

This extended Galilean case study should indicate how far we still have to go to comprehend scientific genius. As an illustration, consider the hypothesized connection between expertise and creativity. The frequently cited 10-year rule obviously has to be dismissed from the outset when dealing with the astronomical discoveries reported in Galileo's 1610 landmark work. There was no expertise to be acquired, and, even if there were, there was no time to acquire it. Instead, the pertinent expertise was being spontaneously generated on the spot—and within a few months, not a full decade. Even worse, the prior knowledge and skill that often proved most useful had no predicable link with the actual discovery. In Galileo's discovery of the Moon's mountains, his cognizance of contemporary optics proved almost useless whereas his skill as a visual artist supported the breakthrough insight. Here I suspect that Galileo is not alone. Whenever scientists make monumental discoveries, they must often use BVSR procedures to create a new expertise on the fly. Indeed, their cumulative discoveries are what establish that expertise for the first time. Successors then have an expertise to acquire that had no prior existence.

The Dutch scientist Antonie van Leeuwenhoek offers a striking parallel example.[8] After experimentally devising an innovative, more powerful microscope of his own unique design—a simple, one-lens instrument—he single-handedly established the science of microbiology. Among his discoveries were protozoa, bacteria, spermatozoa, muscle fibers, the cell's vacuole, blood cells, and blood flow in the capillaries. An untrained tradesman, with no knowledge of optics or any other scientific domain, his discoveries were at first challenged by the scientific "experts," particularly given that nobody could figure out how he made lenses that multiplied minuscule objects hundreds of times (a well-kept secret that was not solved until more than 2 centuries after his death). Just as Galileo recorded celestial objects never before seen using an advanced instrument, Leeuwenhoek's own cutting-edge instrument demonstrated the existence of another wonderful world beyond our unaided vision. Where Galileo invented the field of telescopic astronomy, Leeuwenhoek invented the field of microscopic biology.

The foregoing parallel has a fascinating twist. In 1624, almost a half century before Leeuwenhoek began publishing his discoveries in the *Philosophical Transactions of the Royal Society*, Galileo took an interest in the compound (two-lens) microscope (Van Helden, 2003; Wooton, 2010). Similar to the telescope, the prototype came from Dutch spectacle makers. Galileo played around with the instrument for a while, magnifying bees and other curiosities, showed some of his results to fellow members of the Lincean Academy, and then gave the instrument away as a present to the Duke of Bavaria. That's it! Galileo made no effort to refine the instrument to increasingly greater magnifications. The decisive bigger-is-better insight he had with respect to the telescope did not repeat with the microscope a dozen or so years later. He did not foresee that the wonders in the vast cosmos above had comparable marvels in a miniature realm below. Insight became oversight. Perhaps at 60 years he was too old to venture into novel territory. Or, maybe Galileo was already preoccupied with the epochal *Dialogue Concerning the Two Chief World Systems* that he started writing a few months later. For whatever reason, even in hindsight we can probably overlook his oversight. During a lifetime of discovery, even the greatest scientists can exhibit only so much sightedness.

[8] The public-domain information in this paragraph is readily available in print and Internet sources. In the latter case, a remarkable website dedicated exclusively to Leeuwenhoek is located at http://www.vanleeuwenhoek.com. It is noteworthy that Leeuwenhoek might have had a personal connection with an eminent painter of his time and place—no less a figure than Jan Vermeer. Indeed, Leeuwenhoek may have provided the actual model for two Vermeer paintings of scientists—*The Geographer* and *The Astronomer*. The figure is clearly the same person in both paintings, and the room in which they are painted is obviously the same as well (see also http://www.essentialvermeer.com). Leeuwenhoek himself might have even commissioned the two paintings to compare his microscopic discoveries favorably with the breakthroughs of modern geography and astronomy, the latter likely including Galileo. Coincidentally, Leeuwenhoek was born in the same year that Galileo published the *Dialogue Concerning the Two Chief World Systems*.

References

Amabile, T. M. (1996). *Creativity in context: Update to the social psychology of creativity.* Boulder, CO: Westview.

American heritage electronic dictionary (3rd ed.). (1992). Boston: Houghton Mifflin.

Aristotle (1952). On the heavens. In R. M. Hutchins (Ed.), *Great books of the Western world* (Vol. 8, pp. 359–405). Chicago: Encyclopaedia Britannica. (Original work published c. 350–320 BCE)

Baer, J. (2011). Why grand theories of creativity distort, distract, and disappoint. *The International Journal of Creativity & Problem Solving, 21,* 73–100.

Boden, M. A. (2004). *The creative mind: Myths & mechanisms* (2nd ed.). New York, NY: Routledge.

Brecht, B. (1966). *Galileo* (C. Laughton, Trans.). New York: Grove Press. (Original work published 1952)

Butterfield, H. (1931). *The Whig interpretation of history.* London: Bell & Sons.

Campbell, D. T. (1960). Blind variation and selective retention in creative thought as in other knowledge processes. *Psychological Review, 67,* 380–400. doi:10.1037/h0040373

Campitelli, G., & Gobet, F. (2011). Deliberate practice: Necessary but not sufficient. *Current Directions in Psychological Science, 20,* 280–285. doi:10.1177/0963721411421922

Carson, S., Peterson, J. B., & Higgins, D. M. (2005). Reliability, validity, and factor structure of the Creative Achievement Questionnaire. *Creativity Research Journal, 17,* 37–50. doi:10.1207/s15326934crj1701_4

Cassandro, V. J. (1998). Explaining premature mortality across fields of creative endeavor. *Journal of Personality, 66,* 805–833. doi:10.1111/1467-6494.00033

Cassandro, V. J., & Simonton, D. K. (2010). Versatility, openness to experience, and topical diversity in creative products: An exploratory historiometric analysis of scientists, philosophers, and writers. *Journal of Creative Behavior, 44,* 1–18. doi:10.1002/j.2162-6057.2010.tb01322.x

Colman, A. M. (2001). *A dictionary of psychology.* New York: Oxford University Press.

Derks, P., & Hervas, D. (1988). Creativity in humor production: Quantity and quality in divergent thinking. *Bulletin of the Psychonomic Society, 26,* 37–39.

Dirac, P. A. M. (1963). The physicist's picture of nature. *Scientific American, 208,* 45–53. doi:10.1038/scientificamerican0563–45

Drake, S. (1976). Galileo's first telescopic observations. *Journal for the History of Astronomy, 7,* 153–168.

Drake, S. (1978). *Galileo at work: His scientific biography.* Chicago: University of Chicago Press.

Edgerton, S. Y. (1991). *The heritage of Giotto's geometry: Art and science on the eve of the scientific revolution.* Ithaca, NY: Cornell University Press.

Ericsson, K. A. (1996). The acquisition of expert performance: An introduction to some of the issues. In K. A. Ericsson (Ed.), *The road to expert performance: Empirical evidence from the arts and sciences, sports, and games* (pp. 1–50). Mahwah, NJ: Erlbaum.

Fanelli, D. (2010). "Positive" results increase down the hierarchy of the sciences. *PLoS ONE, 5,* e10068. doi:10.1371/journal.pone.0010068

Feist, G. J. (1993). A structural model of scientific eminence. *Psychological Science, 4,* 366–371. doi:10.1111/j.1467-9280.1993.tb00583.x

Feist, G. J. (1997). Quantity, quality, and depth of research as influences on scientific eminence: Is quantity most important? *Creativity Research Journal, 10,* 325–335. doi:10.1207/s15326934crj1004_4

Fischer, D. H. (1970). *Historian's fallacies.* New York: Harper & Row.

Fischhoff, B. (2007). An early history of hindsight research. *Social Cognition, 25,* 10–13. doi:10.1521/soco.2007.25.1.10

Frensch, P. A., & Sternberg, R. J. (1989). Expertise and intelligent thinking: When is it worse to know better? In R. J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 5, pp. 157–188). Hillsdale, NJ: Erlbaum.

Galilei, G. (1952). Dialogues concerning the two new sciences. In R. M. Hutchins (Ed.), *Great books of the Western world* (Vol. 28, pp. 129–260). Chicago: Encyclopaedia Britannica. (Original work published 1638)

Galilei, G. (1953). *Dialogue on the great world systems* (T. Salusbury, Trans.). Chicago: University of Chicago Press. (Original work published 1632)

Galilei, G. (1960). The assayer. In *The controversy on the comets of 1618* (S. Drake, Trans., pp. 151–336). Philadelphia: University of Pennsylvania Press. (Original work published 1623)

Galilei, G. (1989). *Sidereus nuncius, or The sidereal messenger* (A. van Helden, Trans., with introduction, conclusion, and notes by the Trans.). Chicago: University of Chicago Press. (Original work published 1610)

Galilei, G. (2008). *The essential Galileo* (M. A. Finocchiaro, Ed. & Trans.). Indianapolis: Hackett Publishing. (Original works published 1610–1638)

Gough, H. G. (1979). A creative personality scale for the adjective check list. *Journal of Personality and Social Psychology, 37,* 1398–1405. doi:10.1037/0022-3514.37.8.1398

Grassi, H. (1960). On the three comets of the year 1618. In *The controversy on the comets of 1618* (C. D. O'Malley, Trans., pp. 3–19). Philadelphia: University of Pennsylvania Press. (Original work published 1619)

Gruber, H. E. (1974). *Darwin on man: A psychological study of scientific creativity.* New York: Dutton.

Harris, J. A. (2004). Measured intelligence, achievement, openness to experience, and creativity. *Personality and Individual Differences, 36,* 913–929. doi:10.1016/S0191-8869(03)00161-2

Harris, J. C. (2010). Galileo Galilei: Scientist and artist. *Archives of General Psychiatry, 67,* 770–771. doi:10.1001/archgenpsychiatry.2010.95

Hayes, J. R. (1989). *The complete problem solver* (2nd ed.). Hillsdale, NJ: Erlbaum.

Heilbron, J. L. (2010). *Galileo.* New York: Oxford University Press.

Kaufman, S. B., & Kaufman, J. C. (2007). Ten years to expertise, many more to greatness: An investigation of modern writers. *Journal of Creative Behavior, 41,* 114–124. doi:10.1002/j.2162-6057.2007.tb01284.x

Kirton, M. J. (1976). Adaptors and innovators: A description and measure. *Journal of Applied Psychology, 61,* 622–629. doi:10.1037/0021-9010.61.5.622

Koestler, A. (1959). *The sleepwalkers: A history of man's changing vision of the universe.* New York: Macmillan.

Kronfeldner, M. E. (2010). Darwinian "blind" hypothesis formation revisited. *Synthese, 175,* 193–218. doi:10.1007/s11229-009-9498-8

Mach, E. (1896, January). On the part played by accident in invention and discovery. *Monist, 6,* 161–175.

Maier, N. R. F. (1931). Reasoning in humans: II. The solution of a problem and its appearance in consciousness. *Journal of Comparative and Physiological Psychology, 12,* 181–194.

McAllister, J. W. (1991). Scientists' aesthetic judgments. *British Journal of Aesthetics, 31,* 332–341. doi:10.1093/bjaesthetics/31.4.332

McCrae, R. R. (1987). Creativity, divergent thinking, and openness to experience. *Journal of Personality and Social Psychology, 52,* 1258–1265. doi:10.1037/0022-3514.52.6.1258

Merton, R. K. (1961). Singletons and multiples in scientific discovery: A chapter in the sociology of science. *Proceedings of the American Philosophical Society, 105,* 470–486.

Mitroff, I. I. (1974). Norms and counter-norms in a group of Apollo moon scientists: A case study in the ambivalence of scientists. *American Sociological Review, 39,* 579–595. doi:10.2307/2094423

Murray, C. (2003). *Human accomplishment: The pursuit of excellence in the arts and sciences, 800 B. C. to 1950.* New York: HarperCollins.

Mynatt, C. R., Doherty, M. E., & Tweney, R. D. (1978). Consequences of confirmation and disconfirmation in a simulated research environment. *Quarterly Journal of Experimental Psychology, 30,* 395–406. doi:10.1080/00335557843000007

Nickerson, R. S. (1998). Confirmation bias: A ubiquitous phenomenon in many guises. *Review of General Psychology, 2,* 175–220. doi:10.1037/1089-2680.2.2.175

Ogburn, W. K., & Thomas, D. (1922). Are inventions inevitable? A note on social evolution. *Political Science Quarterly, 37,* 83–93. doi:10.2307/2142320

Osborne, H. (1984). Mathematical beauty and physical science. *British Journal of Aesthetics, 24,* 291–300. doi:10.1093/bjaesthetics/24.4.291

Palmieri, P. (2001). Galileo and the discovery of the phases of Venus. *Journal for the History of Astronomy, 32,* 109–129.

Parnes, S. J. (1961). Effects of extended effort in creative problem solving. *Journal of Educational Psychology, 52,* 117–122. doi:10.1037/h0044650

Perkins, D. N. (2000). *The eureka effect: The art and logic of breakthrough thinking.* New York: Norton.

Pope, T., & Mosher, J. (2009). *What Galileo saw.* Retrieved from http://www.pacifier.com/~tpope

Popper, K. (1959). *The logic of discovery.* New York: Basic Books.

Popper, K. (1963). *Conjectures and refutations.* London: Routledge.

Root-Bernstein, R., Allen, L., Beach, L. Bhadula, R., Fast, J., Hosey, C., . . . Weinlander, S. (2008). Arts foster scientific success: Avocations of Nobel, National Academy, Royal Society, and Sigma Xi members. *Journal of the Psychology of Science and Technology, 1,* 51–63. doi:10.1891/1939-7054.1.2.51

Root-Bernstein, R. S., Bernstein, M., & Garnier, H. (1995). Correlations between avocations, scientific style, work habits, and professional impact of scientists. *Creativity Research Journal, 8,* 115–137. doi:10.1207/s15326934crj0802_2

Simonton, D. K. (1976). Biographical determinants of achieved eminence: A multivariate approach to the Cox data. *Journal of Personality and Social Psychology, 33,* 218–226. doi:10.1037/0022-3514.33.2.218

Simonton, D. K. (1979). Multiple discovery and invention: Zeitgeist, genius, or chance? *Journal of Personality and Social Psychology, 37,* 1603–1616. doi:10.1037/0022-3514.37.9.1603

Simonton, D. K. (1992). Leaders of American psychology, 1879–1967: Career development, creative output, and professional achievement. *Journal of Personality and Social Psychology, 62,* 5–17. doi:10.1037/0022-3514.62.1.5

Simonton, D. K. (2000). Creative development as acquired expertise: Theoretical issues and an empirical test. *Developmental Review, 20,* 283–318. doi:10.1006/drev.1999.0504

Simonton, D. K. (2004). *Creativity in science: Chance, logic, genius, and zeitgeist.* Cambridge, England: Cambridge University Press.

Simonton, D. K. (2009). *Genius 101.* New York: Springer Publishing.

Simonton, D. K. (2010). Creativity as blind-variation and selective-retention: Constrained combinatorial models of exceptional creativity. *Physics of Life Reviews, 7,* 156–179. doi:10.1016/j.plrev.2010.02.002

Simonton, D. K. (2011a). Creativity and discovery as blind variation and selective retention: Multiple-variant definitions and blind-sighted integration. *Psychology of Aesthetics, Creativity, and the Arts, 5,* 222–228. doi:10.1037/a0023144

Simonton, D. K. (2011b). Creativity and discovery as *blind* variation: Campbell's (1960). BVSR model after the half-century mark. *Review of General Psychology, 15,* 158–174. doi:10.1037/a0022912

Standish, E. M., & Nobili, A. M. (1997). Galileo's observations of Neptune. *Baltic Astronomy, 6,* 97–104.

Sternberg, R. J. (1998). Cognitive mechanisms in human creativity: Is variation blind or sighted? *Journal of Creative Behavior, 32,* 159–176. doi:10.1002/j.2162-6057.1998.tb00813.x

Sternberg, R. J., & Davidson, J. E. (Eds.). (1995). *The nature of insight.* Cambridge, MA: MIT Press.

Sulloway, F. J. (1996). *Born to rebel: Birth order, family dynamics, and creative lives.* New York: Pantheon.

Van Helden, A. (1974). Saturn and its anses. *Journal for the History of Astronomy, 5,* 105–121.

Van Helden, A. (1989). Introduction, conclusion, and notes. In Galilei, G. (1989). *Sidereus nuncius, or The sidereal messenger* (A. van Helden, Trans.). Chicago: University of Chicago Press.

Van Helden, A. (2003). *The Galileo Project.* Retrieved from http://galileo.rice.edu/

Weisberg, R. W. (1995). Case studies of creative thinking: Reproduction versus restructuring in the real world. In S. M. Smith, T. B. Ward, & R. A. Finke (Eds.), *The creative cognition approach* (pp. 53–72). Cambridge, MA: MIT Press.

Weisberg, R. W. (2006). *Creativity: Understanding innovation in problem solving, science, invention, and the arts.* Hoboken, NJ: Wiley.

Wertheimer, M. (1982). *Productive thinking* (M. Wertheimer, Ed.). Chicago: University of Chicago Press. (Original work published 1945)

White, R. K. (1931). The versatility of genius. *Journal of Social Psychology, 2,* 460–489. doi:10.1080/00224545.1931.9918987

Wolman, B. B. (Ed.). (1989). *Dictionary of behavioral science* (2nd ed.). San Diego: Academic Press.

Wooton, D. (2010). *Galileo: Watcher of the skies.* New Haven, CT: Yale University Press.

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