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Scientific Method as Cultural Innovation

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Abstract

Consideration of scientific method as a cultural innovation requires examining the philosophy and sociology of science, anthropology, developmental, cognitive, and social psychology as well as the histories of science and technology. Anarchistic philosophical proposals about science set the stage for subsequent endorsements of quite liberal conceptions of science and scientific thinking that root these pursuits in basic features of human—even animal—cognition or in the intimate connection between science and technology. That every methodological prescription has its limits or that science is not uniform does not entail methodological anarchism. Like any other radial category, science includes more and less central instances and practices. Justifications for such liberality regarding science that are grounded in the acquisition of empirical knowledge by infants and other species downplay the sciences' systematic approach to criticizing hypotheses and scientists' mastery of a vast collection of intellectual tools, facts, and theories. Justifications that look to the close ties between science and technology neglect reasons for distinguishing them. Intimate ties are not inextricable ties. Research on scientific cognition suggests that, in some respects, human minds are not well suited to do science and that measures progressively sustaining science's systematic program of criticism and its ever more counterintuitive representations both depend on cultural achievements and are themselves cultural achievements involving what have proven to be comparatively extraordinary social conditions. This richer, epistemologically unsurpassed form of science is both rare and fragile, having arisen no more than a few times in human history.

Introduction

The increasing scope, precision, and sophistication of modern science and its explanatory and predictive successes encompass considerably more than science's barest cognitive essentials. To focus on those at the expense of characterizing progressive scientific traditions downplays the crucial role cultural innovations have played in science's achievements.

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Making this case requires clarifying how much about science comes naturally to human minds. I thus begin by outlining arguments for skepticism about the *scientific method* that have set the stage for recent discussions. It also demands situating positions that (a) construe science as the outcome of natural predilections of mind, emphasizing its continuity with commonsense and (b) fixate on the inevitable entanglement of science with technology. Those accounts are incomplete. The first takes insufficient notice of the elaborate measures necessary to insure critical scrutiny in science and the extensive education required for participating in it, and the second minimizes the vital position that cognitive ideals occupy. These matters are discussed in the first section.

Thereafter, cognitive and historical considerations are presented that favor an accounting of scientific method as cultural innovation. The cognitive science of science urges caution about the Cartesian picture of rationality as residing between matched pairs of human ears. Any constructive account of scientific method and rationality, in the face of myriad shortcomings of individual reasoners, dwells, instead, in the special cultural, social, economic, and political arrangements that undergird modern science. Although scientific sparks and brushfires have erupted sporadically in human history, sustained traditions of disciplined inquiry with institutions fostering methodical criticism are recent, refined, and rare.

Integrating Cognitively Liberal Conceptions of Science

Some philosophers and sociologists of science have disputed claims for scientific rationality and posed problems for a uniform scientific method. Some anthropologists, developmental psychologists, and literary theorists have endorsed liberal accounts of scientific cognition, which can also challenge a view of scientific method as cultural innovation.

Against Method

Although Thomas Kuhn (1970) famously assailed the methodological unity of science, no one criticized it more provocatively than Paul Feyerabend (1975). Both were reacting to decades of armchair philosophizing aimed at rationally reconstructing science in terms of observations and mathematical logic. Both stressed how prevailing programs of research influence the acceptability of methods. Feyerabend, for example, maintained that Galileo's arguments on behalf of the telescope's veracity on Earth—when viewing ships too distant to be seen by the naked eye—were for Aristotelians, who distinguished terrestrial and celestial principles metaphysically, reasons for *doubting* the reliability of telescopic images of heavenly bodies.

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Both also defied the methodological proposals of prominent philosophers. Feyerabend assaulted Karl Popper's suggestion that aspiring to test persistently and falsify hypotheses empirically is what distinguishes science. Feyerabend insisted that this view was unworkable, since *from the outset* scientists know about evidence that is incompatible with new hypotheses. The neutrino hypothesis would have never gotten off the ground, since its first empirical corroboration came more than two decades after Wolfgang Pauli initially proposed it (Dunbar 1995). Shoving leading formulations off their pedestals, Feyerabend suggested the only plausible account of scientific method was "*anything goes*," though, he noted straightaway that not even that slogan was a methodological recommendation.

That contemporary sciences embrace diverse methods and entertain abstruse theories, which often resist ready interpretation, only increases wariness concerning pronouncements about scientific method. The rise of the "Strong Program" in the sociology of science (Bloor 1991) and nonmodernist variants (Latour 1993), which hold that social arrangements fundamentally shape scientific interests and procedures, combined with philosophers' failure to provide compelling accounts of the influence of the superempirical virtues (e.g., simplicity, consilience, elegance) on theory choice have only exacerbated such reservations about an identifiable scientific method.

Managing Methodological Skepticism: Cognitively Liberal Conceptions of Science

Feyerabend's methodological anarchism and sociologists' challenges to scientific rationality created a milieu that pushed the defenders of science toward more modest accounts of its essential intellectual activities. These comparatively liberal accounts construe scientific cognition so broadly as to include not only everyday thinking but also learning in infants and animals.

The Roots of Science

Some Anthropologists' Views. Noting that the sciences employ no "single universally applicable methodology," Robin Dunbar explores more rudimentary cognitive underpinnings, born of "the natural mechanisms of everyday survival" (Dunbar 1995:94, 96). Science involves learning about the world and its causal structure. Dunbar holds that "all higher organisms" carry out "plain simple learning," equipping them with expectations for predicting things well enough to survive and reproduce (Dunbar 1995:77, 75). Thus, he suggests that science's cognitive essentials (i.e., learning inductively, including hypothesis testing) come as naturally to many animals as they do to humans.

One consequence of such liberality is the reluctance of many anthropologists to differentiate science and religion (e.g., Horton 1993). In small-scale

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societies, religions provide the frameworks with which people explain events, whereas in most modern, large-scale societies, science has largely usurped that prerogative, increasingly confining religion to matters of morality as well as social and psychological well-being, at least in public discussion. Such liberalism, however, provides little insight about why, with regard to explaining events, religious worldviews are *not* typically overthrown in the first case and why modern science does just that in the second.

Some Developmental Psychologists' Views. Alison Gopnik, Andrew Meltzoff, and Patricia Kuhl (1999) have advanced the stronger and somewhat less liberal view that scientific progress and human cognitive development, in particular, proceed similarly—that babies are "scientists in the crib." They emphasize that, like scientists, infants are active learners who are sensitive to evidence.

The various looking-tasks that developmental psychologists have devised for ascertaining what babies know assume that they recognize violations of their expectations. At six months of age, infants can detect statistical patterns and draw probabilistic inferences from populations to samples (Denison et al. 2013); fourteen-month-olds can predict single-event probability from large set sizes (Denison and Xu 2009). Three- and four-year-old children make causal inferences based on probabilistic evidence, even when it conflicts with information about spatial contiguity (Kushnir and Gopnik 2007). Facing upended expectations, toddlers and preschool children seek evidence in exploratory play and carry out explanatory reasoning (Legare 2012; Legare et al. 2010).

That infants produce new theories, however, is less plausible, certainly if "theories" refer to scientists' linguistic constructions. Still, findings about prelinguistic infants' growing knowledge surely imply that they do develop new expectations. Gopnik holds that "children's brains...must be *unconsciously* processing information in a way that parallels the methods of scientific discovery" (Gopnik 2010:80, emphasis added). Even if babies qualify as theorizers, though, theorizing is not unique to science, as Horton's observations about religion suggest. Theorizing by young children may be necessary, but it is not sufficient for their activities to count as scientific.

The Critical Side of Science

Scientific Pluralism. Methodological anarchists and the Strong Program sociologists of science have overplayed their hands. Given the range of phenomena that human ingenuity has enabled us to study scientifically as well as the serendipity and hubbub of human affairs in general, it is not shocking that, finally, only vague methodological prescriptions ("attend to evidence;" "pursue overall coherence") will plausibly characterize all productive forms of scientific inquiry. "Science" is a radial category that encompasses numerous

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endeavors that are spread across a vast conceptual space with more and less salient cases along a host of relevant dimensions. Exhibiting scientific rationality in some inquiry may involve conforming to any of a hundred viable principles that collectively cover the central regions of that space well enough to count as proceeding reasonably in empirical investigation. Methodological anarchism hardly exhausts the options for responding to Feyerabend's arguments that no particular, exception-less, methodological recommendation will capture the entire array of activities that we regard as scientific.

Nor do the effects of cultural circumstances on scientific topics, theories, methods, and assessments, let alone training, organization, funding, and institutions, constitute an insurmountable barrier to constructing a case for the reasonableness and epistemic prominence of science. Does anyone contest the suggestion that culture shapes human thought and conduct? *That*, however, hardly establishes that science's progress, empirical findings, or ascendant theories are rationally suspect or that scientists cannot reassess them through further criticism and research. Scientific objectivity resides neither in unimpeachable methods nor in investigators' neutrality.

Situating Cognitively Liberal Conceptions of Science. Dunbar's conjecture that some animals (e.g., rats) carry out hypothetical causal inferences is controversial (Dunbar 1995). Michael Tomasello has argued, for example, that not even chimpanzees recognize underlying causes (Tomasello 1999:22). Dunbar also acknowledges problems about the representational format of hypotheses that animals allegedly adopt (Dunbar 1995).

Introducing a distinction between "cookbook" science and explanatory science, Dunbar signals that, ultimately, the contention that thinking scientifically comes naturally to animals will not bear too much weight (Dunbar 1995:17). The hypotheses Dunbar attributes to animals are about patterns of perceptible events closely associated in time and space. This is cookbook science, which resembles patterns characteristic of human folk physics and folk biology. Following Lewis Wolpert (1992), Dunbar ultimately insists that the factors which have launched the "superpowerful process" of "explanatory science" consist of "features of formal science that do not really exist in the everyday version" (Dunbar 1995:88).

Cognitive liberalism, then, will not account for much that is vital to science after all. Neither inductive capacities nor even the more sophisticated cognition of crib-based scientists explains modern science's wealth of explanatory and predictive accomplishments or the contributions of other eras to the history of scientific knowledge.

Criticism as a Scientific Obligation. What distinguishes science from other explanatory and predictive enterprises is a fixation on *criticism*. Scientists constantly push theories for new empirically testable consequences and for

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coherence internally and externally with the best theories about related matters (Tweney 2011).

Infants, young children, and people in cultures in which science never flowered understand that evidence matters. That, however, is only the beginning. First, that does not establish that they will discern *relevant* evidence. Researchers must know the ascendant theories, their implications, and their competitors to understand what counts as relevant evidence. Evidence is always evidence-relative-to-a-theory.

Without knowing the theories, people will fail to recognize evidence right before their eyes. Correlations between the proximity of islands, their volcanic activity, size, elevation, and more are not difficult to detect in an island chain, but it requires some understanding of the theory of plate tectonics to grasp their evidential status. Without that theory the role those patterns might play as evidence will be obscure, at best.

Second, scientists must systematically collect and record evidence. Getting more and diverse evidence demands assembling and documenting it conscientiously. For some theories and models (e.g., concerning climate), scientists must examine long-term trends in disparate places with considerable precision. Aiming to build definitive star maps, John Flamsteed made hourly measurements of planets and the positions of various stars for *forty years* (Jardine 2000).

Third, scientists are also experts at generating new evidence. Science's idealized theories identify relevant variables that affect a system's behavior over which scientists seek experimental control, when the systems under scrutiny are not so large (or so small) or so complex or so remote that they preclude such interventions. Complicated experimental arrangements and instruments (whether supercolliders, eye trackers, or electron microscopes) play a vital role in science. These devices furnish opportunities to examine phenomena in unfamiliar environments or in what would typically be the inaccessible provinces of ordinary environments where diverging empirical implications of competing theories can be tested. Scientists become skilled experimentalists, producing conditions that differ from typical circumstances *in theoretically significant ways* and for which human natural cognitive inclinations are uninformative and unhelpful.

Fourth, scientists must also analyze and assess the evidence they amass. Obtaining evidence is one thing; knowing what to make of it is quite another. Scientists need facility with several forms of mathematical representation to comprehend theories and to evaluate evidence. The demands of science for treating data systematically to ascertain their evidential import have led to a variety of mathematical tools for their analysis. Mathematical clarity and precision are crucial for exploring, measuring, and dissecting the dynamics of complex systems.

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Liberalism Inspired by Science's Connections with Technology

Science and technology have always been connected, but since the mid-nineteenth century, they have become practically inextricable. Scientific advances routinely depend upon devising machinery for creating special environments for testing hypotheses. More familiar are the increasingly widespread technologies that modern science has created, including everyday gadgets. Teasing theoretical science and its methods apart from technology *conceptually* runs the risk of appearing to underplay this intimate connection.

Is Technology Inherently Scientific?

Technological Grounds for Cognitive Liberalism. Barbara Herrnstein Smith correctly holds that theoretical understanding routinely depends on technologies implementing theories and that new technologies just as routinely provoke new explanatory conjectures. Consequently, she asserts that to separate science and technology so straightforwardly involves a "narrow, historically and culturally quite specific, understanding of 'science'" that results in a distinction that "can only be arbitrary and artificial" (Smith 2009:132, 135). Envisioning technology as inherently scientific also motivates cognitive liberalism about science. Smith's cognitive liberalism includes *as scientific* all production and use of technology by human groups.

Perhaps the distinction is artificial, but that does not mean that it is not useful. A variety of independent considerations demonstrate that it is not arbitrary (see discussion in the next section). Examining science's *cognitive* foundations provides grounds for distinguishing it from technology and for curtailing this version of liberalism too.

An Alternative View of the Intimate Relation between Modern Science and Technology. Ironically, Smith's charge that a sharp distinction between science and technology is "narrow" and "historically and culturally...specific" seems to concede its applicability to modern science, *in which their connections seem more profound than ever*. John Gribbin, who opens his history of modern science with the observation that technological developments are more important than scientific genius in the genesis of science, offers a more nuanced account of their relationship that not only does not preclude a clear distinction between science and technology but, in fact, assumes it (Gribbin 2003:xix). Gribbin (2003:xx) states: "Technology came first, because it is possible to make machines by trial and error without fully understanding the principles on which they operate. But once science and technology got together, progress really took off." He then highlights their autocatalytic relationship, which the industrial, electronic, and digital revolutions have only accelerated. Technology may be a necessary condition for the pursuit of science, but it does

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not follow that the most noteworthy cognitive features of science depend upon technology.

Science as Cultural Achievement

The constructive case for cleaving science and technology segues into a larger examination of science as cultural innovation. Considerations from across the disciplines suggest that cognitive liberalism regarding science is incomplete at best. In light of liberal proposals, it is ironic that more than three decades of research in the cognitive science of science suggests that not even scientists, when operating in isolation, are wonderfully impressive scientific thinkers! Diverse factors point to the paramount position culture has occupied in the development of science.

Science is one of many knowledge-seeking activities that humans undertake, but as a continuing, systematic endeavor to explain the world, it is *unsurpassed*. It is "science" in this sense that is pivotal from *both an epistemological and an historical point of view*. Consequently, it will prove equally decisive in reflection about its status as a *cultural* innovation.

Teasing Science and Technology Apart

Science is that unsurpassed knowledge-seeking activity not because of what it has in common with material technology but because of what sets it apart.

History Matters

Ancient History. The ties that bind contemporary science and technology make it difficult to envision circumstances without such ties (because, for example, science did not exist). Two historical observations spotlight technology's cognitive independence from science. The first is science's historical scarcity. Even on inclusive conceptions, science has bloomed infrequently and flourished even less. If the list of continuing scientific activity were to include (a) ancient cultures—Chinese, Babylonian, Egyptian, and Mayan—by virtue of their astronomical record keeping and cosmological speculations, (b) ancient Greeks, (c) Arabs and Chinese during the last centuries of the first millennium through the Middle Ages, and (d) Europeans in the sixteenth and seventeenth centuries and the emergence of modern science that their work inspired, that list would include but a fraction of human history in a much smaller fraction of human societies.

Prehistory. This second consideration is the obverse of the first. Science's rarity contrasts starkly with the ubiquity of technology. *Every* culture possesses technology. The birth of science in human history contrasts with technology's

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prehistoric origins. Prehistoric technologies surfaced independently of science and predate ancient civilizations by a couple of million years among our earlier ancestors. This prehistoric pattern of technology thriving without science has persisted in most places at most times since. That science is required to guide technological progress is a very recent notion.

Natural History. Consider two further facts about *natural history*. First, archaeology has disclosed at least a half dozen other species that produced and used technology. Second, not even the members of our genus, indeed not even primates, have a monopoly on the production and use of tools. Animals—from chimpanzees to New Caledonian crows—both fabricate and use tools (Weir et al. 2002; Kenward et al. 2005). Unlike the pursuit of science, the construction of artifacts is not uniquely human, though, admittedly, the ongoing improvement of tools over generations does seem to be an accomplishment peculiar to species among our genus and a particularly well-established dynamic of human cultural change.

Science as an Abstract Technology

Broad conceptions of technology that include *abstract* intellectual tools as well as implements and structured environments cast science and technology's relationship differently, but justify distinguishing them nonetheless. If written representations count as a technological genus, then science is one of its species. It stands apart from material technology, however, in two notable ways: (a) science, unlike material technology, depends upon literacy and (b) it always includes abstract theoretical interests in understanding nature for its own sake. The latter raises two issues.

Seeking Understanding. Science pursues and explores accounts of the world for their intrinsic interest. If science began with ancient societies' systematic collections of astronomical observations, then it probably arose from practical concerns about calendars. Still, the ancient Greeks differed crucially from earlier astronomers, because they valued reflection about the world for its own sake, regardless of practicalities. The Greeks were the first to discuss theories critically, to marshal empirical evidence, and to advance competing theories. Whatever practical advances it may spawn, science is also always about gaining a deeper understanding of the world.

Toby Huff cites such considerations, when arguing that the Chinese did not develop a scientific tradition, despite their consummate technological innovation and sophistication. Huff holds that their focus remained overwhelmingly practical and that institutions supporting empirical criticism of theories never emerged. Aside from a brief period in ancient China among the Mohists, the Chinese never established a sustained tradition of scientific investigation (Boltz et al. 2003). Although the Chinese had the printing

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press many centuries before Europe, education focused on memorization of Confucian classics (Huff 1993:279).

Impracticality. Scientific pursuits always involve *speculations* that aim to elucidate the world's workings and no other human endeavor recognizes that fact so self-consciously. Scientific speculations depict idealized worlds (of frictionless planes, classical genes, and rational consumers) that go *beyond* what is known, supplying insights about real patterns behind the appearances that enable us to make sense of the world. Those idealized models also have implications for how unexplored parts of the world should prove to be. In these respects, they take seemingly impractical, intellectual risks. They discuss entities, processes, and relations that are removed from practical problems and all previous experience.

Clarification: Cognitively Unnatural Technologies of Modern Science

Most technologies that modern science engenders are as cognitively inaccessible as its theories. Laypersons are unaware of the theoretical underpinnings of the structures and operations of these technologies. This encompasses both the experimental apparatus of science and familiar machines (e.g., cell phones).

The practical benefits of these technologies play an undeniable role in the cultural prestige of science. Science's epistemic standing rests largely on the fact that the sciences regularly enable us to do things that once seemed impossible: from finding oil miles below Earth's surface to transplanting organs, to sending spacecraft to distant planets. Only with science were these envisioned, let alone realized. All of this is quite removed from what most people do with eggbeaters, elevators, and exit ramps. On these fronts, the technologies that contemporary science spawns also stand apart.

Cognitive Reflections

A tradition of criticizing theories systematically requires that scientists become proficient with the requisite intellectual skills. A decade of scientific training is necessary for novices to gain control of these tools and to begin to appreciate the subtleties of their employment. That is because their acquisition and application call for thought and practices which do *not* come naturally to human minds.

Deductive and Probabilistic Inference

Wason. The Wason selection task famously demonstrated how dismally people perform when carrying out conditional inference (Wason 1966). Around eighty percent of participants go wrong. This, alone, should substantially dampen optimism about the naturalness of scientific reasoning, for scientists

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are always reasoning hypothetically: exploring a theory's implications, contemplating some mechanism's operation, or pondering some nexus of causal variables. Subsequent research on the Wason selection task seems to corroborate that in nearly all settings, conditional inference is reasoning that most humans do not do well (Cosmides and Tooby 2005).

Tversky and Kahneman. Estimating the likelihood of events about which scientists have incomplete information is pivotal in explanatory theorizing, argumentation, and decision making. Amos Tversky and Daniel Kahneman have shown that humans' intuitive judgments under conditions of uncertainty routinely transgress normative principles of probability. Scores of studies have disclosed that people neglect such considerations as regression to the mean and base rate information, fail to attend to sample sizes when weighing the significance of evidence, and disregard basic principles of probability theory (Kahneman 2011).

A collection of cognitive shortcuts, which humans consistently take, explain these and other failures. Such biased heuristics serve for most purposes, but their inexact solutions are inappropriate for most scientific jobs. Most of the exotic circumstances in which scientific experiments take place contravene the presuppositions of such heuristics; consequently, these heuristics render us susceptible to *perceptual and cognitive illusions* in many circumstances. These heuristics feel so right that not even monetary incentives for correct answers boost participants' performance (Camerer and Hogarth 1999). Similarly, neither substantive expertise nor advanced training in probability and statistics overcome these natural tendencies. For example, there was "no effect of statistical sophistication" in how participants performed on ranking the probabilities of conjunctions and their conjuncts. In Tversky and Kahneman's experiments with such problems, more than eighty percent of "highly sophisticated respondents" provided rankings that violated the dictates of probability theory (Tversky and Kahneman 2002:26).

Other Cognitive and Psychological Obstacles

The cognitive science of science has uncovered an assortment of additional intellectual pitfalls which can trip up those with scientific training.

Intrusive Intuitions often Swamp Science's Radically Counterintuitive Representations. Usually sooner rather than later, the sciences inevitably generate radically counterintuitive representations that do not square with our folk conceptions of the world. Learning scientific models and principles that contradict heuristics' deliverances, however, does not undo those deliverances. We are Copernicans, yet few ever see the sky that way (McCauley 2011). Experimental research with people who have passed physics courses reveals that many retain numerous false assumptions about basic motions (McCloskey

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1983); thus, ordinary phenomena pose perceptual, explanatory, and predictive problems *that usually go completely unrecognized* (Liu and MacIsaac 2005). Practice with hundreds of textbook problems does not assure that students overcome the conceptual difficulties associated with basic mechanics (Kim and Pak 2002). Elementary problems do not trick experts, but without opportunities to apply their knowledge of relevant formulae, experts' intuitions for motions like collisions are often incorrect (Proffitt and Gilden 1989). Formal education helps, but the knowledge is remarkably fragile.

Confirmation Bias. Psychological and historical research discloses inquirers' penchant to exhibit confirmation bias, which can take a variety of forms. Besides attending only to confirming evidence, scientists can be disinclined to search for contrary evidence and sometimes disregard it when it appears. History is replete with otherwise distinguished scientists who defended problematic theories, insisting that failures to replicate their positive findings resulted from others' carelessness (Gratzer 2000). Theorists cling to their theories and ignore alternatives, particularly when considering the import of unfavorable evidence. When given the choice, instead of seeking information that would bear on the comparisons of theories, experimental participants would pursue "pseudodiagnostic" information, which would neither support their favored theory as they thought nor support such comparisons (Mynatt et al. 1981).

Motivated Perception. Motivated perception concerns the impact that commitments to theories can have on perception. Adherence to a scientific theory means seeing the world in a particular way. Armed with theories, we find them hard to shake. After the ascendance of Copernicanism, European astronomers observed changes in the firmament that the Aristotelian conception had ruled out as impossible. Chinese astronomers, without telescopes but also without the burden of Aristotelian cosmology, had recognized such changes centuries earlier.

Cultural and Historical Reflections

Unfortunately, nature has not groomed human minds for carrying out science's obligatory criticism of theories. Learning and doing science demand grasping intellectual constructs and procuring cognitive skills that humans find difficult to acquire, onerous to retain, challenging to exercise, and unnatural all around. (Experimental science involves a host of practical skills that are no less challenging.) These psychological findings do not support the Cartesian picture locating Reason within individuals' minds. Science's epistemic prominence does not arise from guarantees about individuals' exemplary thought and conduct but from a host of sociocultural arrangements.

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How Have Humans Managed to Do Science?

Science proceeds because of the insistence on the public availability of scientific work and on opportunities to criticize it. To figure in the history of scientific inquiry, sooner or later (sometimes after their death), scientists must offer statements of their positions and the evidence for them for public scrutiny by the scientific community. Copernicus permitted the publication of his *De Revolutionibus* only after his death. That inevitable publicity assures that the criticism of scientific work never need turn on the reliability of any individual's cognitive processing. Individual scientists may be blind to the weaknesses of their theories, the gaps in their evidence, the mistakes in their reasoning, and the errors in their calculations. They may also manifest a decided preference for evidence that supports their hypotheses. Fortunately, the history of science provides ample testimony to the fact that scientists suffer far fewer failings when it comes to assessing positions that compete with their own. It is that public competition in which the partisans and other scientists uncover a theory's failures and problems.

Literacy. That astronomical protoscience ("protoscience" because, among other things, it was subservient to state religions) arose in the first literate cultures is no coincidence. Beyond record keeping, the expectation that scientific work must become publically available links science to literacy. Written symbols last. Literacy permits the storage of ideas, relieving demands on memory. Literate people can return to documents after long delays and retrieve knowledge. The resuscitation of the texts, topics, and theories of ancient Greek science ignited new projects of research that resulted in new scientific developments in substantially different cultural settings, namely in both the Arab world of the tenth century and, again, in Renaissance Europe with the eventual birth of modern science. Documents are critical aids to thought, permitting clarity and precision almost nonexistent in speech but imperative for presenting and testing scientific theories. They are a prerequisite for the careful, systematic, extended criticism that characterizes science. Copied, published, and transported texts introduce the possibility of widespread access to ideas that is beyond their authors' control, which is decisive for the objectivity of science. Scientists discuss the contents of externalized texts, rather than the contents of their creators' mental states. All of these considerations counsel greater caution about what we write than about what we say, and although science is not only about what gets written and published, it is always finally about that.

The opportunity to criticize written, publically available theories occasions the development of intellectual skills that exceed doing arithmetic or the mere decoding of text. Publically accessible exchanges tend toward standardized forms to make positions and reasoning clear. This was as true about the exchanges of the medieval schoolmen as it is about those of contemporary scientists. What the emergence of the empirical sciences adds to these

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procedures of rational, literate inquiry is a particularly disciplined approach to the collection, generation, analysis, and assessment of empirical evidence and of experimental evidence, in particular. To do that effectively requires years of education and training.

Education. Science depends upon the invention of external linguistic and mathematical symbols and an educational system that engenders facility with such symbols in numbers sufficient to generate a *community* of inquirers. Preserving and transmitting such proficiencies require ample investments in an educational infrastructure. Like literate humans, scientists are made not born. Both call for appropriate materials and years of tutelage. Participating in science at its highest levels routinely requires more than twenty years of formal education. This type of education is a uniquely modern phenomenon, which remains confined primarily to the wealthiest half of the world's nations.

Science has been rare in part because literacy (and numeracy) has been rare. The reinvention of the printing press in Europe predated the rise of modern science by less than two centuries. It introduced the possibility of widespread literacy, the proliferation of schools, and the dissemination of scientific works. Most cultures in history did not possess a system of writing and only a fraction of those that did produced a substantial corpus. An even smaller fraction of those produced science.

How Has Science Achieved Its Celebrated Epistemic Status?

This is not a substantive question about settled scientific views but a procedural one about how science works. *Scientific communities* have erected safeguards to catch and correct errors. In addition to the public availability of scientific controversies, two principles deserve special mention.

Peer Review. Scientific journals make extensive use of peer reviewing. Expert, independent referees provide editors with written reports laying out their reservations about scientific papers. Even published authors must nearly always incorporate additional arguments and analyses to meet their referees' objections.

Ideally, that is how the system works. Research indicates, however, that referees treat papers with which they agree more gently than those with which they disagree, which sometimes leads to inappropriate decisions. The process is by no means perfect (Armstrong 1997).[1] Still, scientific communities retain an unending interest in self-improvement, which has led to innovations such as the Public Library of Science. Science must deal with fraud and deceit, but no human pursuit does remotely as good a job of uncovering deceptions. Science has developed good procedures for smoking such ruses out, at least eventually.

[1] For analyses and extended discussion, see http://www.nature.com/nature/peerreview/debate/

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Replication. Science requires the replicability of results. It does not tolerate secret formulas, special sensitivities, or "singularities." Scientists must report on intersubjectively available phenomena. They must describe their experiments at a level of detail that permits other scientists to reproduce them. Failure to replicate findings instantly clouds their credibility. Although its critical examination may wax and wane, until some finding is replicated (ideally, by its critics), its position remains thoroughly provisional. Even often-replicated findings remain susceptible to questioning, which is to say that under at least some circumstances their status is only somewhat less provisional.

Public availability of scientific claims, peer review, and demand for replicability are three important pillars that support the epistemic credibility of scientific methods. The sciences' pattern of explanatory, predictive, and technological triumphs and the accelerated pace of those triumphs over the past century only burnish that standing.

How Has Science Progressed?

The public availability of scientific works insures that science remains a *social* endeavor, which is the key to its long-standing pattern of theoretical and practical triumphs. Although science provides no guarantees, its continuing success depends on its inherently social character. Knowledge, criticism, and decision making are collective accomplishments, distributed across the community (Solomon 2001). Science is inherently social and therefore inherently institutional.

Universities. The gradual development of independent universities proved a critical variable buttressing science's long-term success in Europe (Grant 1996). Late Medieval universities deemed natural philosophy a legitimate component of advanced education, positioning it so that it would be open to upheavals when new theories and methods began to change the terrain three centuries later. They developed standardized curricula, which would eventually serve for credentialing, and supported scientific research.

State-supported, institutionalized experimental science arose in the ninth and tenth centuries in Baghdad and persisted for two centuries in a few locales in the Islamic world (Al-Khalili 2011). Medieval Arabic science, however, never enjoyed a lasting alliance with educational institutions independent of Islam, which has generally proven less congenial than Christianity to scientific education. Without political cover from local rulers, scientific institutions had short lives. For example, Nasr al-Dīn al-Tūsi's observatory and school at Marāgha only thrived for sixty years before falling into disrepair.

Scientific Societies and Disciplines. Institutional arrangements that secure the openness, publicity, and integrity of scientific research were critical to the

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rise of modern science (Jardine 2000:316). Scientific institutions, such as national academies, articulate and enforce standards.

Experimentation and systematic observation carry crucial implications for social and economic arrangements. Modern science requires vast sums to support exotic infrastructure and to probe unusual environments. By the early eighteenth century, some European governments and companies were investing in expeditions to the far reaches of Earth for strategic advantages and profitable ventures, certainly, but for gathering data and specimens and testing scientific hypotheses as well.

Since the middle of the nineteenth century, science has become a fount of knowledge and technical innovation. New social arrangements and infrastructure have enhanced scientific productivity. In addition to schools providing general science education, diverse organizations (professional societies, university departments, journals, laboratories, research institutes, foundations, government and corporate funding) have enabled large numbers to learn and do science. These arrangements facilitate communication, disseminate scientific work, and institutionalize compensatory strategies for handling individual scientists' fallibility. Not even the resulting bureaucracies have been able to undo the fact that most of the time these measures have insured that the collective outcome in the long run is superior to the efforts of individuals in the short run.

Science's Fragility

Science as an unsurpassed method for acquiring empirical knowledge depends on a combination of cultural elements, including literacy, long-term education, freedom from religious and political repression, many peculiar institutions, and substantial resources for theoretical research. For many reasons, including both its cognitive unnaturalness and the obvious difficulties with sustaining such arrangements, this combination is both historically rare and inherently fragile.

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