Gerald Doppelt
Professor of Philosophy UCSD

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Scientific Revolutions

Largely as the result of Thomas Kuhn's work, the concept of scientific revolution gains an importance in post-positivist philosophy of science that it lacks in the dominant logical empiricist tradition of the twentieth century. Kuhn's notion of scientific revolution becomes wedded to a historical relativism concerning scientific knowledge that many have sought to refute, or overcome with new accounts of knowledge that go beyond positivism and relativism.

THE CONCEPTION OF SCIENTIFIC REVOLUTION IN TRADTIONAL PHILOSOPHY OF SCIENCE

To set the context for these debates, it is useful to begin with the ordinary concept of scientific revolution and understand why it lacks fundamental epistemological significance in traditional philosophy of science. In ordinary parlance, a scientific revolution is a large-scale change in the fundamental concepts, theories, or methods that scientists in some area of inquiry employ to understand the course of nature (e.g., the Copernican revolution in astronomy). Such a change is also thought to be revolutionary in so far as it provokes similarly dramatic alterations in the way lay-people see the world. As such, the notion is obviously important to historians of science and popular culture. On the other hand, scientific revolution is not a central topic for the tradition of logical positivism (more broadly, logical empiricism) that generates the key figures, problems, and models of philosophy of science for most of the twentieth century.

In this tradition, the aim of philosophy of science is to provide analyses of the standards most vital to science as the best exemplar of empirical knowledge: the standards of scientific method, confirmation, prediction, falsification, explanation, truth, progress, observation, law, and theory. The philosopher's analyses are supposed to be timeless, normative, universal, non-historical, and non-empirical. To this end, logical empiricists employed the tools of logic and semantics to illuminate the a priori formal structure of all genuine scientific knowledge (such as explanation, and confirmation). Science is identified with its most successful theories, which in turn are represented as finished bodies of propositions linked by logical and inferential relations connecting sense experience to the higher reaches of law and theory.

From this perspective, scientific revolutions alter the content of successful theories, but not the logic of scientific rationality and knowledge. Indeed, the empiricist's logical standards (e.g., Carl Gustav Hempel's deductive-nomological model of explanation, prediction and confirmation) provide the grounds for evaluating the scientific revolutions of Copernicus, Galileo, Johannes Kepler, Sir Isaac Newton, and Albert Einstein. This entire development could be reasonably represented as a logical, cumulative progress. On the philosopher's standards, this progress is one in which, for example, better confirmed theories of wider explanatory scope replace lesser predecessors, whose errors are corrected, and whose sound results are preserved and extended by their successors. The history of the best science(s) illustrates but does not alter the logic of scientific knowledge. So understood, the rationality of science makes it possible for humankind's best theories to converge on the truth concerning law-like regularities in the world of observed phenomena and, perhaps, the underlying, unobservable entities and mechanisms causally responsible for these regularities.</p>

<p>These achievements of logical empiricism gain one of their last, most lucid and systematic reformulations in Hempel's *The Philosophy of Natural Science*. This work

appeared in 1966 four years after Kuhn's *The Structure of Scientific Revolution (SSR)* . Of course many philosophers besides Kuhn challenge one or more of the presuppositions of traditional philosophy of science and reshape the debates in the post-positivist period (e.g. William Van Orman Quine, Wilfred Sellars, Norwood Hanson, Stephen Toulmin, Micheal Scriven, Nelson Goodman, Paul Feyerabend, Mary Hesse, etc.). But Kuhn's challenge in S*SR* is probably unique in the avalanche of criticisms, rebuttals, and new approaches to the history and philosophy of science that it provokes for decades. Much of this response focuses on Kuhn's notion of scientific revolution and the incommensurability, relativism, and irrationalism it is taken to imply.

KUHN'S CONCEPTION OF SCIENTIFIC REVOLUTION

In effect, Kuhn mobilizes a new conception of the history of science, in which scientific revolution is fundamental and its nature contradicts the formal rationality, normativity, universality, logicism and progressive cumulativity sought by logical empiricists, and still embraced in new forms by contemporary philosophers (e.g.. scientific realists). The philosophical thrust of Kuhn's notion of scientific revolution can be tersely expressed as the following claim. It is in the very nature of (a) science that it undergo not simply changes in the content of its theories, but more fundamentally changes in the very language, problems, goals, and standards that (re)-define science, the criteria of scientific knowledge, and membership in the scientific community. This sort of change is what Kuhn's conception of scientific revolution implies, an epistemological change in the requirements of scientific knowledge, explanation, proof, and confirmation. The claim that the essence of science is to generate scientific revolutions, in its own epistemological self-definition, seems like a general philosophical claim. But it is not an a priori claim, for Kuhn. Rather the claim is supposed to be justified by showing that it provides the best explanation of the actual development of science, which opens it up to criticism on this score. In any case, this argument gives history a central role in the evaluation of a philosophy of science.

Kuhn's view of scientific development turns on its division into periods of normal science marked by a normative consensus in the scientific community concerning how to conduct inquiry; and periods of scientific revolution, marked by the breakdown of this consensus. Revolutionary periods typically end when the scientific community is redefined on the basis of a new consensus that creates a different framework for normal science. The normative consensus required by normal science involves the existence of a paradigm that all experts accept as the basis of their research. A scientific revolution implies the dissolution of one paradigm and its eventual replacement by another. A paradigm is a concrete solution (e.g., Lavoisier's account of combustion) to a particular problem (why do some substances gain weight in combustion) that members of a scientific community commonly recognize as an exemplar of how to pursue inquiry in a wider domain of phenomena (chemical reactions); phenomena that may prove to be of the same or similar kind as the paradigm first treated. A group of inquirers only becomes a scientific community when their research generates a paradigm. As the central object of normative consensus, the paradigm guides practitioners in commonly recognizing what counts as a legitimate problem or phenomenon-to-be-explained in the domain of their science. It tells them what concepts, techniques, mechanisms, measurements, and standards must be present for a legitimate solution to the problem, a bona fide scientific explanation of it. Normal science is the research undertaken to articulate and extend the paradigm by solving a host of puzzles that arise in the attempt to reduce ever-wider phenomena to its terms.

In this process, the shared commitments of the scientific community grow and encompass the formulation of theories, laws, basic equations, standards of proof, mathematical techniques, and experimental procedures. In some contexts, Kuhn refers to this entire body of commitments as the paradigm. Normal science allows a cumulative progress of scientific knowledge, but it is progress within the paradigm, relative to its standards of puzzle solving and explanation. Normal science breaks down when the paradigm confronts anomalies**.** Anomalies are problems that it ought to be able to resolve, but over time cannot, and that motivate some practitioners to represent the problem, or attempt solutions in ways that abandon basic components of the paradigm and the normative consensus underlying the research tradition defined by it. For Kuhn, one of the best examples of scientific revolution is the abandonment of the premodern chemistry of the phlogiston theory and the theory of elective affinity, due to Lavoisier's oxygen theory of combustion and the new compositional paradigm of Daltonian chemistry.

KUHN'S CONCEPTS OF INCOMMENSURABLITY

Phlogiston chemistry succeeded in explaining many qualitative phenomena with a paradigm that posits the existence and properties of phlogiston (the presence of phlogiston solves the problem of why the metals have common metallic qualities lacking in their ores). But the phlogiston theory explained the combustion of a substance as a loss of phlogiston that implied weight loss. The phenomenon of weight gain in combustion constituted an anomaly for phlogiston theory because despite serious attempts, no phlogiston chemist succeeded in accounting for it within the constraints of this paradigm. As inquirers abandoned different components of the phlogiston paradigm, in order to accommodate the phenomena of combustion, the road was paved for a revolutionary transformation in the very concepts, language, questions, techniques, data, values, aims, and standards at the heart of chemistry. In *SSR*, Kuhn stresses the discontinuities marked by scientific revolution and advances his most controversial claim that these discontinuities imply incommensurability between the paradigms or theories separated by scientific revolutions. Incommensurability seems to imply that pre- and postrevolutionary theories cannot be compared because there is no common measure to ground comparison. Such a view is at opposite poles from the project of logical empiricists and their heirs to establish a framework of concepts and standards external to particular theories and their history, and capable of grounding critical evaluation, and judgments of cognitive progress.

But there are different lines of argument in Kuhn concerning the sources and implications of incommensurability. Rival theories are said to be incommensurable because (1) they do not share the same language, or conceptual scheme, and the language of one is not translatable into the language of the other, or a neutral observation language; (2) they do not perceive or recognize the same observational data; (3) they do not address or acknowledge the same problems; (4) they do not embrace the same standards of theory-evaluation or the same interpretations of standards; and (5) they do not live in the same world. While all of these claims are present in Kuhn's argument, which of these sources of incommensurability is most basic, or most defensible? How much room does it leave for continuity and commensurability at the other levels of scientific development? These questions raise the issue of what role reasoning plays in Kuhn's conception of scientific revolution, and how large a role is played by psychological and sociological processes.

Kuhn's very notion of a paradigm and a paradigm-change is sociological in so far as it involves the collective mechanisms through which a scientific community builds up and protects a shared allegiance to its norms and social control over who is and is not a member. He characterizes scientists' embrace of a new paradigm in psychological terms as a gestalt-switch, a leap of faith, and a conversion experience. What role, if any, is left for reason (confirmation, proof, prediction, falsification) in scientists' acceptance of (1) a new conceptual scheme, (2) a new domain of observational data, (3) a different agenda of problems, (4) different standards of theory-evaluation, or (5) a novel world? Which of these is the most basic source of incommensurability? Kuhn's readers and critics focus on different strands of this account of scientific revolution and in response, move philosophy of science in different directions.

THE FIRST WAVE OF CRITICS: INCOMMENSURABLITY AS TOTAL MEANING CHANGE AND EXTREME REALITIVISM

The first influential line of criticism (Isreal Scheffler 1967, 1972, Dudley Shapere 1964, 1966, 1971) takes Kuhn's notion of scientific revolution to rest on a radical, holistic conceptual relativism and an implausible view of systematic meaning-variance between paradigms and theories. In essence, on this reading, the first alleged source of incommensurability, paradigms' unique untranslatable language of science, is taken to imply all the others, incommensurabilities of data, problems, standards and worlds. Each scientific paradigm is imprisoned within its own framework of theoretical concepts whose internal relations determine the unique meaning of each concept and all observation terms employed by the paradigm. On this reading of Kuhn, scientific revolutions change the meaning of all concepts employed by the exponents of a paradigm (e.g., planet in the Copernican revolution) and no translation is possible between the rival languages of science. With no language in common, it is easy to see why Kuhn would also hold that rival paradigms cannot share common observational data, problems, standards, or worlds. But in that case the advocates of rival paradigms cannot communicate or argue and thus their commitments (beliefs, values, etc.) must be explained by non-rational psychological and sociological processes. Furthermore, retrospective evaluations of theories of the sort grounded in the criteria of traditional philosophy of science (degree of confirmation, explanatory scope, etc.) will be impossible; because there will be no neutral language that permits comparisons of their empirical content. Thus Kuhn's concept of scientific revolution leads to a radical incommensurability and extreme relativism, on which every paradigm, or research tradition, is justified on its own terms, and none is any better than another (better confirmed, etc.).

For the first wave of Kuhn's critics, the resulting position of Kuhn's analysis is incoherent and a "reduction" of its own premises. If rival paradigms cannot be compared or communicate in a common language, in what sense are they rivals? With no common subject matter, there is nothing for them to disagree about. In that case, there would be no difference between a shift of paradigms (or scientific revolution) within a scientific discipline (Cartesian to Newtonian physics) and the movement of inquirers from one area of inquiry into an entirely different one (physicists becoming neuroscientists). Furthermore, Kuhn's notion of anomalies implies that rival paradigms share some common observational data about which they disagree, and which allow comparisons of their empirical content and success. In that case, they must share some concepts or language, undermining the thesis of radical conceptual incommensurability. Finally the holistic conception of scientific meaning depends on a failure to distinguish sense and reference, among other flaws. Even if the reference of a concept changes ("planet" from Ptolemy to Copernicus; "mass" from Newton to Einstein), there may be sufficient stability of connotation to yield commensurability. On the other hand, when the connotation of observational concepts (temperature of a gas) changes, there is often sufficient stability of reference to allow comparison of paradigms' empirical contents. The development of causal theories of reference reinforced the arguments for continuity of reference (Phillip Kitcher 1978, Stathis Psillos 1999).

This entire line of criticism located the failure of extreme relativism and radical incommensurability within the terrain of philosophy of language and Kuhn's false starts there. It convinced many philosophers of science that whatever its problems, the tradition of logical empiricism had little reason to worry about Kuhn's notions of scientific revolution and incommensurability.

INCOMMEASURABLITY AS SHIFTS-IN-STANDARDS

A second reading of Kuhn shifts the focus to the strain of argument that bases incommensurability not on language, but rather on shifts in the epistemic standards or values that accompany scientific revolutions (Gerald Doppelt 1978, 1980**,** John Zammito 2004). Such changes transform the criteria of theoretical knowledge and successful inquiry, for the field and scientific community in question. An allegiance to the new standards implicit in a paradigm shift typically involves a redefinition of the domain of problems and observational phenomena most important for any adequate theory to explain. These shifts sometimes generate losses in the problem-solving capacity and explanatory power of science, though the epistemic importance of these losses is evaluated differently on the disparate standards implicit in rival paradigms.</p>

The premodern chemistry of the phlogiston theory and the theory of elective affinity generated solutions to a large number of problems that are eliminated from the domain of phenomena-to-be-explained by the modern chemistry instigated by Antoine-Laurent Lavoisier and John Dalton. It could account for the observable properties of a number of substances, solving the problem of why metals exhibited common metallic qualities, lacking in their ores, and why metals take on acidic qualities as a result of chemical reactions. While such questions could still be formulated in the nineteenth century, the failure to answer them, to explain the observed qualities of compounds, is not taken as a cognitive defect in Daltonian chemistry; even though empirical success with these phenomena was a central criterion of theoretical knowledge for premodern chemistry. Of course the modern chemistry of Lavoisier and Dalton succeeded in solving a whole range of problems (concerning weight relations and proportions in chemical reactions) that were largely unknown until their work. Still given Kuhn's "loss-of-data" and "shift-in-standards" arguments concerning scientific revolution, on his view, the Daltonian paradigm is not well characterized as simply offering a better, truer, or more rational account of chemical phenomena than its predecessor. For, the premodern and modern paradigms provided explanations of different sorts of observed phenomena, in accordance with different problem-sets, and in line with different standards of adequacy for chemical theory.

Reading Kuhn's argument in this way generates a more moderate notion of scientific revolution, incommensurability, and relativism than the initial critics identified.

The argument is compatible with considerable continuity and overlap across paradigms concerning language, observational data, problems, and even standards. The existence and role of anomalies exhibits such overlap. More generally, this reading is compatible with Kuhn's clear recognition that new paradigms often try to, and succeed at, treating many of the phenomena at the heart of their predecessors, and satisfying some of their standards, as well as their own. What, then, is left of incommensurability and relativism, in moderate form? Is there a moderate form of these doctrines?

On the moderate version of Kuhn, advocates of rival paradigms present good reasons and arguments to one another. But because their disagreement is about the standards of their science, and the strength of reasons is relative to such standards, paradigm debates and shifts (scientific revolution) are often marked by an absence of compelling reasons. Equally scientific and rational inquirers can weight the balance of good reasons in contradictory ways that favor the standards and achievements implicit in their rival paradigms. This moderate notion of incommensurability of reasons generates a distinctive Kuhnian version of the underdetermination of theory by evidence. Antirealists often argue that the observational implications of a theory do not confirm the truth of the theory. Because one can always imagine another theory T1, incompatible with T, with the same confirmed observational implications; the two theories are empirically equivalent but cannot both be true. Realists reply that evidence and confirmation involve more than the mere logical consequences derivable from the theory. Confirmation of a theory by evidence for many realists requires that the theory provide the best explanation of the evidence, in virtue of its simplicity, accuracy, explanatory scope, fruitfulness, plausibility, and unification. Kuhn acknowledges the universality of such epistemic values in science. But he argues that shifts-in-paradigms change the criteria governing their application and their relative importance in determining the best explanation. Premodern and modern chemistry both valued unifying explanation, but embraced different standards concerning what sorts of phenomena required unified explanation.

If theory, or paradigm choice, is underdetermined by evidence, and good reasons, due to Kuhn's shift-in-standards claims, reason (scientific method) alone will not explain scientific revolution. Without glorifying irrationalism or mystical conversion, Kuhn can vindicate the relevance of psychological and sociological factors to explain which particular scientific considerations, in an ocean of conflicting reasons, prove compelling to the practitioners who accept a new paradigm, and why. Moderate relativism thus asserts that scientific development involves revolutions in which a new paradigm triumphs, even though it entails some losses in problem-solving capacity, and is no more rational to accept than its predecessor(s), given the different standards at play in the historical context.

CRITICS OF MODERATE RELATIVISM

This more moderate version of Kuhn's conception of scientific revolution moves its evaluation away from the philosophy of language onto the terrain of epistemological argument. Various critics of Kuhn's shift-of-standards relativism advance arguments based on the existence of external standards, piecemeal bootstrap scientific rationality, naturalist epistemology, and scientific realism (discussed, in turn, below). In the spirit of logical empiricism, some critics argue that Kuhn's emphasis on internal paradigm-specific standards is fully compatible with the existence of external, universal, and non-relative standards of scientific rationality and progress; such as predictive accuracy, explanatory scope, simplicity, completeness, empirical success, unifying power, and the like (Scheffler 1967). Isn't the existence of such independent standards what makes rational debate between exponents of rival paradigms possible and indeed intelligible as such to us today (Harvey Siegel 1980, 1987)?

Kuhn fully embraces the existence of such universal epistemic considerations (empirical success, etc.) in science. But he argues that they function as broad, abstract values of scientific inquiry, whose actual contents are transformed by scientific revolutions. In effect, he takes a moderate relativism of internal standards to imply a relativity of external standards to paradigms. But this is not supposed to be an a priori claim about scientific development. Kuhn's studies of normal science, revolution, and scientific debate are supposed to show that exponents of rival paradigms apply the aforementioned epistemic values in very different ways, yielding concretely different standards of explanation, simplicity, unification, and even accuracy (what counts as an acceptable measure of experimental deviation of prediction from observed result).

But does Kuhn's moderate relativism concerning the role of reasons and standards in scientific revolution imply any relativism concerning long-run scientific progress? The tradition of logical empiricism concerns the context of justification, not discovery. As long as there are external standards of theory-assessment sufficient to establish that science overall attains cognitive progress, Kuhnian short-run losses in problem-solving and standards need not imply any global relativism. As Kuhn himself observes these losses are often recouped in the long-run. Though the chemical revolution initiated by Lavoisier abandons the effort to explain the qualities of compounds, these problems are taken up and resolved in twentieth century science. Newtonians first accepted and later abandoned the Aristotelian and Cartesian standards requiring a mechanical explanation of motion, thus gravity (no action-at-a-distance). Einsteinian physics produces an explanation of gravity without any loss to the data and problems handled by Newtonian science.

Kuhn explicitly claims that scientific development exhibits progress in the sense that there are dramatic increases in the number, range, variety, and accuracy of its problem-solutions (even if it is not consistently cumulative, step by step). Another critic seizes on problem-solving effectiveness as the way to accommodate Kuhn's historical insights while overcoming his relativism concerning scientific rationality and equivocations about cognitive progress (Larry Laudan 1977). He seeks to establish an external standard of problem-solving effectiveness with a theory-neutral calculus for identifying, counting, and weighing the various empirical and conceptual problems tackled, solved, and unsolved in rival or successive research traditions. This account follows Kuhn's historicism in allowing that rival research traditions (a looser, more flexible concept than paradigm) are often committed to different problems, different standards of solution, different criteria for individuating, counting, and weighing important kinds of conceptual and empirical problems. By accepting the historical relativity of problems, solutions and standards, the externalist model of maximal problem-solving effectiveness runs the risk of collapsing into a Kuhnian moderate relativism concerning the rationality of scientific change and cognitive progress. For example, on the externalist model, the objective importance of a problem (how much it affects a tradition's problem-solving effectiveness) is elevated if rivals tackle and solve it. Against this criterion, the problem solutions taken to be most important in establishing the chemistry first, of Lavoisier, and later, of Dalton, address phenomena that were largely unknown to premodern chemists (e.g., the alchemists) and thus should enjoy less epistemic weight than they were accorded and needed in the making of the chemical revolution. Once external standards are historicized, relativism threatens.

A second critique of Kuhn's notion of scientific revolution follows Kuhn in rejecting self-sufficient external standards and embracing a historicized account of scientific rationality, but one without relativist implications. These critics argue that there are typically good reasons for altering the standards and goals of scientific inquiry, internal to the historical context of shared beliefs in which the change occurs. If the context of shared belief can provide inquirers with a justification for preferring some standards over others, then paradigm change is in principle entirely rational and explainable by the reasons in its favor, without recourse to psychological and sociological dynamics (Siegel 1980, 1987). Some philosophers adopt a multi-level, piecemeal, and gradualist model of scientific change to show precisely how and why the background context of scientific change provides inquirers with good reasons to make these changes (Laudan 1984, Shapere 1984).

The gradualist model directly challenges Kuhn's holistic historiography of normal and revolutionary science. Normal science is supposed to be ordered by a global framework of tightly interwoven concepts, problems, theories, standards, and aims, such that change of any one component implies alterations in all the others. Scientific revolutions are supposed to imply something like a sudden and wholesale break with the entire framework (extreme incommensurability and relativism), or at least its alleged foundational standard(s) (moderate relativism), and the acceptance of a wholly new one.

Gradualist critics argue that if this is what scientific revolutions are supposed to be, then either there are not any, or very few. The process of rebuilding the framework of scientific inquiry is piecemeal and gradual. Change at one level - whether it is theoretical beliefs, empirical observation, methodological standards, or broad cognitive aims - does not dictate change at all other levels; and no one level is foundational for all the rest (Laudan 1984). On the other hand, change on any one of these levels can be justified by elements of continuity and agreement at other levels, even if we accept the Kuhnian view that there are no sacrosanct or permanent aims and standards with which to anchor justification (Shapere 1984).

To take a well-known example, consider the decision of inquirers during the nineteenth century to abandon an exclusive commitment to the Newtonian standard of inductive generalization, which ruled out the epistemic rationality of using observation to support inference to unobservable entities and processes. The strict empiricist inductive standard of proof was widely thought to be responsible for the great Newtonian achievement and its decisive methodological break with the vacuous, speculative hypotheses of Cartesian physics. But in the eighteenth and nineteenth centuries, scientific practitioners became increasingly interested in explaining well-known electrical, chemical, magnetic, gravitational, optical, and other sorts of observed phenomena. This set of aims took their inquiries beyond the strictures of the Newtonian empiricist standard. The most successful theories George Lesage, David Hartley, Roger Boscovitch) of these phenomena posited the existence of an unobservable ether(s) in order to account for them. The scientific credibility of these problem-solutions, turned on a new standard of theory-assessment, the method of hypotheses (hypothetico-deductive reasoning). Scientists like Lesage defended this standard as a sound route to genuine knowledge, alongside inductive empiricism. Some members of the scientific community became increasingly committed to the aim of explaining these phenomena, outside the privileged domain of Newtonian physics, and to the aether theories that realized this aim. These shared commitments provided good reason to defend the method of hypothesis and abandon inductivism as the sole standard of genuine knowledge (Laudan 1981, 1984).

The other theorists are neither practitioners of normal Newtonian science nor participants in a revolutionary break with it. They do not question the Newtonian achievement and do not reject the standards and aims associated with it. By justifying a wider standard of inference than Newtonians allowed, the aether theorists grounded the empirical success of their theories and enhanced the internal consistency of their commitments. Scottish natural philosophers like Thomas Reid stuck to the Newtonian standard and thus argued that the ether theories could not embody genuine scientific knowledge. If one thinks of the parties to these debates as members of the scientific community, then it is much more loosely structured that the notion of a paradigm implies. Its members have different levels of commitment to the disparate components of the framework of scientific inquiry at the time. The framework itself may exhibit tensions or inconsistencies that different inquirers seek to resolve in different ways. The gradualist model of scientific change exploits cases like this to show how the historical context provides inquirers with good reasons for embracing a new standard of scientific knowledge.

Some philosophers press the gradualist model further to argue for a historical conception of progressive scientific rationality on which reasoning over time produces dramatic improvements in the standards, methods, and goals of good reasoning itself. For example, ether theories are ultimately discredited, and the method of hypothesis is supplanted by more demanding criteria of abduction (e.g., William Whewell's consilience of inductions). Nonetheless, the ether theorists' defense of an inference to unobservables, to account for observed phenomena, improved subsequent scientists' understanding of how knowledge can be achieved and what form it might take. Scientific development can thus be understood as a process of learning how to learn, one in which reasoning generates progressive historical improvements in the very goals, methods and standards of good reasoning itself (Leonard Briskman 1977, Harold Brown 1977, Laudan 1984, Tom Nickles 1993, Shapere 1984, Zammito 2004). Such accounts of scientific rationality are characterized as bootstrap rationality, the internalization of reasons, evolutionary epistemology, or non-relativist historicism, depending on which version is at issue. This dialectical growth in scientific rationality itself accounts for a feature of science that Kuhn himself acknowledges<em>the extraordinary increase in the power of science, what it can do, by way of problem-solving effectiveness, prediction, explanation, and control. If scientific development implies the enlargement of one's very capacity to reason, this account blunts the epistemological force of Kuhn's notion of scientific revolution (shifts-in-standards, moderate relativism).

THE TURN TO NATURALSM AND REALISM

A closely related development is the emergence of naturalized epistemology. The project of naturalistic epistemologists is to characterize scientific knowledge and its methods on the basis of empirical inquiry, not historical narrative of any sort. Scientific method can be characterized as whatever processes of inference are in fact most effective and reliable means to the ultimate aims of science. Some normative naturalists treat the history of science as a body of empirical evidence that can be used to determine which scientific aims are in fact realizable, and which methods are most effective in realizing them (Laudan). Reliabilist naturalists appeal to our best current sciences in order to determine which methods or mechanisms of belief-formation are most reliable in producing true beliefs (Alvin Goldman 1988). From the naturalists' standpoint, scientific change and new standards are not evaluated by the internal reasons provided by the historical context to the inquirers reasoning in that context. Rather naturalists appeal to external empirical knowledge in order to determine whether reliable and effective methods have been followed and this determination does not depend on the reasons or standards that inquirers themselves employ. From this standpoint, rational change and progress in science are evidenced by increases in the reliability of its methods and theories in generating true beliefs.

This naturalistic turn provides another way of circumventing Kuhn's notion of scientific revolution and the historical relativism (of reasons) it implies. One problem for naturalist epistemology arises from the plurality of aims or values in scientific inquiry, a central point in Kuhn's work. The naturalist cannot be expected to identify effective and reliable methods, or processes, of scientific inquiry, if its aim is left indeterminate. Is the aim explanation or prediction, maximal accuracy or unification, simplicity or completeness, etc? Even if one settles on a unitary aim such as truths about the world (as reliabilists hold), this does not settle the methodological debate between realists and empiricists, or instrumentalists. If the aim is theoretical truths concerning the unobservable causes of observational regularities, as scientific realists argue, then they may also be correct in treating inference-to-the-best explanation as the most effective and reliable method. If the only realizable aim is exclusively truths at the observational level itself, or instrumental reliability (as empiricists stress), then other methods may be more effective. Indeed, the debate between empiricists and realists is precisely over the reliability of inference-to-the-best explanation as a method of confirming the truth of theories. While there are good arguments on both sides, they are not mainly the sorts of purely empirical considerations that naturalist epistemology speaks to. They are closer to the normative and conceptual disagreements brought to light by Kuhn's conception of scientific revolution **(**Dopplet 1986,1990, 2001**)** .

Indeed Kuhn's conception places him squarely on the side of instrumentalists. His conception allows that science exhibits cognitive progress in the sense that our best current theories possess vastly more empirical success, instrumental reliability, and problem-solving effectiveness than their predecessors. For scientific realists, the great empirical success of our best current theories provides compelling evidence that they are true. If they weren't true, so realists argue, their great success would be a miracle (Boyd 1973, 1984, 1992, Putnam 1975, 1978, Psillos 1999). The realist view of theories provides the best explanation of their success. On the other hand, Kuhn takes his conception of scientific revolution to support an uncompromising antirealism. He sometimes claims that a scientific revolution alters the world, or more weakly, the aspects of the world central to scientific perception and inquiry (Hoynigen-Heune 1993). In addition, scientists' standards of success and truth shift in scientific revolution. For these reasons, scientific revolution is supposed to preclude the cognitive progress of theories toward the truth concerning the underlying, unobservable structure of reality.

Between Kuhn's virulent antirealism, and the argument of current scientific realists, there is a fundamentally different view of which features of science are most important to account for. Kuhn's notion of scientific revolution focuses on shifts in standards and aims. Scientific realists emphasize the remarkable success of our best science in realizing the ambitious standards and aims it has. If what is most important to explain is not how science arrived at its current standards and aims, but rather why the best current theories are so successful in realizing them, then scientific realists' account offers a powerful antidote to Kuhn's relativism.

Yet, scientific realists have not been entirely immune to Kuhn's historicism. One of the most influential criticisms of scientific realism stems from a careful consideration of past science (Laudan 1984). The realist appeals to the truth, or approximate truth of our best theories, to explain their empirical success. But how will the realist explain the fact that many outdated theories (e.g. the luminiferous ether theory of the propagation of light) were also empirically successful but false, to the best of our knowledge. Indeed, doesn't this record of false but successful theories constitute good inductive evidence that our currently most successful theories are also probably false? In response, scientific realists have turned to these historical cases and provided realist accounts of their successes and failures (Psillos 1999). Taking stock of the history, realists seek to narrow the range of truly successful theories, limit the components of theories confirmed by their success, and secure a greater continuity of reference than Kuhnian revolutions allow.

However its merits are finally judged, Kuhn's conception of scientific revolution drove a very fruitful wedge between traditional philosophy of science and historicism. It realigned the relation of philosophy of science both to the history of science, and studies of specific scientific practices, theories, and controversies. This realignment helped bring a fuller range of sciences such as biology into the purview of philosophy of science, where physics once reigned supreme. The debates inspired by Kuhn's work helped generate the new approaches to scientific method, rationality, and progress previously described. All told there is more than a little irony in the fact that some of the most vocal and relentless critics of Kuhn's notion of scientific revolution ended up learning, and teaching, the most from it. What first appeared to many as Kuhn's revolution of irrationality, later proves to be a central component in a larger process of rethinking the aims and methods of philosophy of science itself.

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