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The Nature of Scientific Progress

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I. Introduction

The concept of scientific progress has long been a subject of philosophical inquiry. Thomas Kuhn's influential account in *The Structure of Scientific Revolutions* proposes that science advances not through a steady accumulation of knowledge but via paradigm shifts. He describes science as moving through alternating phases of "normal science," where scientists work within established paradigms, and "revolutionary science," where a crisis leads to a paradigm shift. Although Kuhn's view shifted the understanding of how scientific fields develop, it also sparked debates, especially regarding his radical portrayal of paradigm shifts and the implications for scientific progress. This essay critically examines Kuhn's account, arguing that his conception of paradigms is too radical and underestimates the diverse motivations behind scientific inquiry, including practical engineering objectives and serendipitous discoveries. Through this analysis, the essay advocates for a broader understanding of scientific progress as the fulfillment of goals rather than merely shifts in paradigms or solving puzzles within paradigms.

II. Kuhn's Paradigm Shift and the Nature of Scientific Progress

Kuhn's concept of scientific progress challenges the traditional view that science advances steadily toward an objective truth through the accumulation of knowledge. Instead, he argued that scientific progress occurs through paradigm shifts, in which one framework of understanding is replaced by another that addresses the anomalies left unresolved by the previous paradigm. Progress in science, for Kuhn, is not linear or cumulative, nor does it necessarily bring us closer to an absolute or overarching truth. Rather, it involves shifts in the way scientists interpret and organize knowledge within their respective fields.

Kuhn considered progress in science to occur when one paradigm replaces another because the new paradigm offers better solutions to the problems or anomalies that the previous paradigm could not adequately address. Importantly, this does not imply that the new paradigm is "truer" in an ultimate sense (Kuhn, 1962, p. 170), but rather that it is more effective for solving the specific puzzles that scientists encounter within the new framework.

He emphasized that each scientific revolution brings a new paradigm that redefines what is considered a valid scientific problem, method, and solution. For example, when Newtonian mechanics replaced Aristotelian physics, it provided a fundamentally new way of understanding motion, forces, and the natural world. Newtonian mechanics would later be replaced by quantum mechanics and Einstein relativity.

According to Kuhn, there are three primary focuses or tasks of factual scientific investigation during periods of *normal science*. One focus of normal science is to gather and determine facts that are significant within the framework of the prevailing paradigm. Scientists conduct experiments or make observations that allow them to establish precise data, which may help confirm the existing theory. For instance, in classical mechanics, determining the exact values of gravitational constants or measuring planetary orbits would be examples of fact-gathering that reinforces the paradigm. The emphasis is not on challenging the existing theory but on discovering facts that further substantiate and elaborate on it. The second focus is on ensuring that empirical data aligns with theoretical predictions. In normal science, scientists work to reconcile observed facts with the expectations set by the paradigm. If there are discrepancies between the observed facts and the theoretical predictions, scientists try to adjust the theory in minor ways or improve experimental methods to ensure a better fit between theory and observation. This task involves ensuring that facts are consistent with the paradigm's explanatory models. The third focus involves the clarification and elaboration of the theory itself. This includes making the theory more precise, extending its applications to new phenomena, or developing mathematical formulations that better articulate the paradigm’s principles. In this phase, scientists work on resolving ambiguities or refining the paradigm’s scope to cover more specific cases or phenomena that were previously less understood. This essay aims to show that these are not the only way normal science is conducted.

Alongside challenging Kuhn's concept of normal science, this essay will also examine one of his central insights: the incommensurability of paradigms. According to Kuhn, paradigms are not directly comparable in terms of their concepts and methods, as there is no overarching objective criterion - such as a universal truth - by which to judge the superiority of one paradigm over another. As Kuhn himself asks, “What could ‘evolution,’ ‘development,’ and ‘progress’ mean in the absence of a specified goal? To many people, such terms suddenly seemed self-contradictory” (Kuhn, 1962, p. 172). This raises a fundamental question: what does "progress" mean in science, and how can it be understood? This essay aims to provide a new perspective on the progress of science.

III. Radical Paradigm Shift

In considering the issues with Kuhn's work, one of the most significant critiques is his portrayal of paradigms as too radical and all-encompassing. Kuhn describes paradigms as essentially exclusive: when a scientific revolution occurs, the new paradigm overtakes the old, leaving the previous framework behind. He suggests that scientists who continue to work within the old paradigm are left on the margins of the scientific community, forgotten and unable to contribute meaningfully to progress. Additionally, normal science is only about solving puzzles within a paradigm. He states "mopping-up operations are what engage most scientist throughout their careers" (Kuhn, 1962, p. 24). However, this account of paradigms seems overly dramatic and, in many cases, inaccurate, especially when we consider how science actually operates in practice.

In fields like chemistry, for instance, we consistently see multiple paradigm models coexisting and being used interchangeably depending on the specific goals of the researcher. Different models for molecular bonding, the Lewis structure and Molecular Orbital (MO) theory, provide a striking example of this. A Lewis structure is a diagram that represents the bonding between atoms in a molecule and the distribution of valence electrons around them. It was developed in 1916 by Gilbert N. Lewis in his article "The Atom and the Molecule". It uses dots to show lone pairs (non-bonding electrons) and lines to represent bonds (shared electron pairs). The structure follows the octet rule, meaning each atom aims to attain 8 electrons. It shows how atoms achieve stable electron configurations by sharing or transferring electrons. This theory was created when understanding of chemical bonding was still limited. Due to its exceptionally simplistic nature, this theory is still often used by chemists today, despite it's limitations. For example, the Lewis structure of oxygen is unable to predict the paramagnetic behaviour of oxygen.

Molecular Orbital (MO) theory, grounded in quantum mechanics, provides a more comprehensive and detailed understanding of chemical bonding compared to the Lewis structure. First quantitatively developed by Lennard-Jones in 1929, MO theory explains bonding by describing how atomic orbitals, treated as wave functions, combine to form molecular orbitals that extend across the entire molecule (Lennard-Jones, 1929). These molecular orbitals are classified as bonding, antibonding, or non-bonding, depending on their impact on the molecule's stability. MO theory is able to explain the paramagnetic behaviour of oxygen, as it predicts oxygen having two unpaired electrons in it's electron shell, unlike the Lewis structure which predicts the electron to be paired.

In terms of Kuhn's framework, Lewis structures and Molecular Orbital (MO) theory can be seen as distinct paradigms because they represent different approaches to understanding and explaining molecular bonding. A paradigm, in Kuhn's sense, encompasses a set of assumptions, methods, and problem-solving strategies shared by a scientific community. The Lewis structure paradigm, for instance, operates within the framework of the octet rule and assumes that chemical bonds can be adequately represented by shared and lone pairs of electrons. In contrast, MO theory reflects a paradigm grounded in quantum mechanics, offering a more sophisticated and mathematically rigorous explanation of bonding. Electrons, although both theories use the same term, are understood differently. Electrons is Lewis' theory is understood as point particles. Electrons in MO theory have an additional property, their quantum number, m_s, called the spin projection quantum number, can either be positive or negative. Only the m_s that are of opposite signs can pair together. Electrons from MO theory are also situated in orbitals and have specific rules for how they occupy those orbitals. These rules are given by the Pauli exclusion principle.

These differences show that the Lewis structure and MO theory are incommensurable (as Kuhn would describe, each operates on its own set of principles and theoretical assumptions) and can be considered paradigms in the prediction of chemical bonding. Despite this, they are not seen as rivals that seek to replace one another but as complementary tools. Chemists do not discard the Lewis structure because of their incommensurability with the quantum mechanical based model of MO theory; instead, the model is chosen that best serves the current needs. Even within a single research group whose goal is to study specific molecules, both models will be used. Lewis structures are also taught to new students well before introducing MO theory. The Lewis diagram of the valence electrons gives quick basic insights into which molecules will potentially bond together, and it is reasonably accurate. It is still the most widely used model of chemical bonding (Lower, n.d.) because of its simplicity and intuitiveness. Quantum mechanical models are used for higher accuracy and far greater scope of use (inorganic bonds can be predicted using quantum mechanical models based on MO theory which Lewis structures cannot). however, they are severely more complicated for creating predictions.

Although both models continue to be used in the scientific community, Kuhn's concept of paradigm shifts suggests older models, like the Lewis structure, would no longer play an active role after a new paradigm emerges. Kuhn describes normal science as the process of refining knowledge within a single paradigm, which raises a question: if the shift to MO theory represents a new paradigm, why do Lewis structures still play such a significant role in scientific practice? Importantly, while the theoretical foundations of Lewis structures are no longer being actively developed, the model remains a fundamental tool for scientific research. If Kuhn's framework does not account for the continued use of older paradigms in parallel with newer ones, it suggests a limitation in his description of scientific progress.

Friedman touches on this issue by arguing that previous theories are not entirely outdated or irrelevant as Kuhn implies. He argues that there is an intellectual continuity between paradigms, even during scientific revolutions. He introduces the idea of a meta-framework, which allows for rational discourse between paradigms and ensures that earlier theories are not entirely discarded as the connection allows earlier paradigms to remain comprehensible and relevant within newer paradigms, often as special cases or approximations within the broader framework of the successor paradigm.(Friedman, 2001). However, this perspective does not adequately explain why different paradigms, like the Lewis structure and MO theory, coexist in practice. The Lewis structure cannot be seen as an approximation to MO theory in the same sense that Newtons Euclidian space, which was the a priori basis for the classical laws of motion, is an approximation to Einsteins curved space. The continued use of the Lewis structure is not about theoretical continuity but about pragmatic utility. The model remains essential for predicting and testing reactions, particularly in organic chemistry, because of its simplicity and practical effectiveness. For example, Lewis structures help chemists propose mechanisms and design experiments that lead to significant discoveries about molecular behaviour, even if the model itself is no longer being refined. This pragmatic coexistence of paradigms highlights an area that Friedman's framework does not fully address: the enduring use of older paradigms as tools in scientific practice, not because of theoretical continuity, but because they continue to serve specific practical purposes better than newer, more complex paradigms like MO theory.

IV. Normal Science and its Presumed Boundaries

It is not evident that normal science is solely concerned with working within a paradigm, whether through fact-gathering, aligning empirical data with theoretical predictions, or refining the theory as explained in section II. This perspective appears overly restrictive and assumes that the goals of scientists and research groups are confined to advancing the paradigm model itself. Such an assumption overlooks the diverse motivations behind scientific work. Practical necessities, unforeseen discoveries, and the pursuit of immediate applications frequently drive scientific progress. These motivations demonstrate the complexity of scientific practice, where researchers are not merely puzzle-solvers within a theoretical framework. Similarly, Friedman also limits his focus to scientific activity as operating within paradigms structured by constitutive a priori principles, emphasizing their role in shaping scientific inquiry and transitions. However, like Kuhn, his account does not adequately address the broader motivations and practicalities that drive much of scientific progress beyond theoretical paradigms.

Engineering provides a particularly illuminating example of scientific work that does not aim to further a scientific theory but instead operates with concepts and models that serve purely practical purposes. Unlike scientific theories, which are generally developed to resemble or explain reality as accurately as possible, engineering models are tools crafted for functionality. They do not need to mirror the complexities of the real world; they simply need to yield reliable, workable results. For instance, the use of fluid flow models, such as the film model in chemical and mechanical engineering, exemplifies this pragmatic focus. These models offer a simplified representation of fluid behaviour to optimize processes in industrial design. Engineers working with these models are not primarily concerned with their accuracy as descriptions of fluid dynamics on a molecular level but rather with their utility in achieving desired outcomes. The film model, in fact, does not accurately represent many aspects of fluid behaviour. It goes beyond an idealized abstraction of reality – such as neglecting air resistance in projectile motion – to being fundamentally incorrect in its resemblance to reality (Song, 2023). Nevertheless, it provides engineers with a practical tool for calculating flow rates, heat transfer, and other relevant parameters in a manageable and effective way.

This emphasis on pragmatism over theoretical refinement illustrates that engineering often operates outside the realm of paradigm-driven science as described by Kuhn in his concept of normal science, even though it may still draw upon the same constitutive a priori principles. While normal science focuses on solving puzzles within an existing theoretical framework to advance a paradigm, engineering models and tools are developed and selected primarily for their functionality, reliability, and simplicity, irrespective of whether they contribute to theoretical understanding. In the development of materials for structural integrity, mathematical models used to predict strength are often entirely empirical, lacking a direct theoretical basis in the physical sciences. These models are not valuable because they elaborate on paradigms such as atomic structures or bonding; rather, they are instrumental in enabling engineers to predict and manage practical outcomes. Consequently, engineering relies on empirical, idealized, abstract, or even theoretically incorrect models that may not advance paradigmatic science but can significantly influence scientific and technological progress through their utility in achieving practical objectives. Practical utility may be the primary goal of the engineer, but it is not the only alternative pathway for scientific progress. Science can also advance unintentionally, without deliberate intent.

Some of the most significant advances in science, especially in chemistry, happen through accidental discoveries, which again challenges the view that scientific progress is necessarily tied to a systematic resolution of puzzles. The discoveries of Kevlar and Teflon, both accidental in nature, are prime examples of this phenomenon. Kevlar, a high-strength polymer used in bulletproof vests and numerous other applications, was discovered accidentally by Stephanie Kwolek while working on a new lightweight fibre for tires. Similarly, Roy Plunkett's discovery of Teflon, now known for its non-stick properties and wide use in various industries, occurred when he was trying to develop a new refrigerant. Neither of these discoveries emerged as solutions to existing puzzles in chemistry, nor were they the result of deliberate attempts to advance the paradigms governing polymer science. Instead, they were unforeseen outcomes that opened up entirely new avenues of research and application in materials science. While these accidental discoveries did not fit neatly into any existing paradigms at the time, nor were the akin to anomalies of any paradigm, they were nevertheless transformative. In this case, there was no specific goal that was achieved, however, it is seen as progress because it paved the way for other goals to be achieved.

V. What is Progress in Science?

Kuhn's account of scientific progress is limited in his suggestion that science lacks goals beyond the internal workings of paradigms and puzzle-solving. He states "Perhaps the most striking feature of the normal research problems we have just encountered is how little they aim to produce major novelties, conceptual or phenomenal" (Kuhn, 1962, p. 35). Kuhn's model implicitly assumes that science progresses without any overarching or purposeful direction, beyond solving puzzles within paradigms until anomalies trigger a crisis and a new paradigm emerges. Which means that paradigm shifts cannot be straightforwardly called "progress" because, according to him, paradigms are incommensurable i.e. meaning they operate under different rules, assumptions, and methods that are not directly comparable. Since each paradigm defines its own standards of success and validity, there is no common measure to objectively judge one paradigm as closer to the truth than another.

Friedman offers a more nuanced conception of scientific progress that challenges Kuhn’s view of incommensurability and radical breaks between paradigms. He argues that scientific progress occurs through rational transitions facilitated by meta-frameworks, which preserve the intelligibility of earlier paradigms within newer ones as explained earlier. This creates a sense of intellectual continuity even during revolutionary shifts. Additionally, Friedman introduces the concept of the relativized a priori, which refers to historically contingent principles that structure scientific inquiry within a given framework. Progress involves the refinement and evolution of these principles, allowing science to expand its explanatory scope over time. For example, while Newtonian mechanics was replaced by Einstein’s theory of relativity, the former remains a valid limiting case under certain conditions, illustrating how earlier frameworks are integrated into and reinterpreted within broader paradigms. In this way, progress is not a matter of radical replacement but the cumulative expansion of scientific understanding.

This view does not account for the broader ways in which “normal science” can be conducted, as explained in the previous section. Progress is still achieved even when “normal science” does not directly aim to expand the theoretical framework of the current paradigm. For instance, the continued use of a previous paradigm, such as Lewis structures, does not fit within the concept of theoretical expansion but instead serves as a practical and efficient tool. The question would be how is it possible in Friedmans conception of progress, that the constitutive principles of the Lewis structure framework is still advancing science even though it has no intellectual continuity with MO theory or can be considered part of a broader understanding of molecules? This is why I argue that progress instead must be seen as the achievement of the niche goals set by scientists. Theoretical frameworks, whether considered current paradigms or not, should be considered a tool for doing so. From this perspective, paradigm shifts can indeed be considered progress, but not because they replace one paradigm with another. Instead, progress in science is reflected when the goals set by researchers doing normal science are attained whether they were working on expanding the theoretical framework of the current paradigm or not and whether they were using the currently accepted constitutive principles of that paradigm or not.

VI. Conclusion

Scientific progress cannot be fully explained by Kuhn’s concept of radical paradigm shifts or Friedman’s idea of intellectual continuity. The coexistence of paradigms like Lewis structures, which lack intellectual continuity with Molecular Orbital (MO) theory, and MO theory demonstrates that progress often arises from practical applications and diverse uses rather than the complete replacement or seamless expansion of one framework by another. Recognizing that progress is driven by the achievement of specific goals set by scientists, rather than being confined to the boundaries of Kuhn’s "normal science," allows for a more comprehensive understanding of scientific development. Theoretical frameworks and models function as tools to achieve these goals rather than as definitive measures of progress. Science, therefore, advances through the attainment of specific objectives—whether they are theoretical, practical, or accidental—rather than solely through paradigm shifts or theoretical refinements.

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