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The Counterfactual Paths and Their Convergence in the History of Physics, Science, and the World

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In her groundbreaking paper, Léna Soler (2023) explores a counterfactual historical scenario in which an interpretation of quantum physics, similar to that of David Bohm (1952), is taught everywhere at the university level, following its victory over what we now refer to as the Copenhagen interpretation (or the Copenhagen orthodoxy). She meticulously investigates the descriptive, formal, and ontological disparities between these two interpretations, presenting a compelling case for the plausibility of such an alternative historical trajectory.

Alternative Paths to the Foundation: Counterfactual Histories of Physics

Let us illustrate just the following two key distinctions between these approaches to quantum theory:

> 1. The orthodox view favors formal minimalism, emphasizing the active role of the observer in quantum measurements, while the Bohmian account offers a perspective of "subject-detachability" more aligned with a traditional notion of objective observations.
>
> 2. The Copenhagen interpretation incorporates both particles and waves as fundamental elements, whereas the Bohmian interpretation emphasizes fundamental particles guided by (metaphysical?) waves.

Soler refrains from asserting that Bohm's or indeed any Bohmian-like interpretation is necessarily superior in philosophical and physical terms, a stance that some philosophers, though very few physicists, might claim these days. Instead, she maintains the view that an alternative trajectory was indeed feasible.

Studies of counterfactual history in the realm of physics or science, generally, are quite rare. Soler (2016) co-edited a collection titled *Science as It Could Have Been: Discussing the Contingency/Inevitability Problem*. However, discussions about what constitutes indispensable components of scientific knowledge and which aspects are contingent make up only a small fraction of the sub-field known as History and Philosophy of Science. Surprisingly few philosophers and historians of science delve into counterfactual histories, even though, as I will argue, they may hold the key to understanding what truly matters in the scientific process. They can serve as a valuable framework for comprehending present and future trajectories of scientific development.

It is intriguing that Soler's focus lies in challenging the conventional *teaching* of quantum mechanics based on the broad consensus of the Copenhagen interpretation. This interpretation, often referred to as orthodoxy, represents a somewhat loose amalgamation of theories, experiments, and philosophical narratives, suitable for introductory university-level teaching. In many cases, this narrative merely scratches the surface and fails to align with the nuances embraced by the theory's original physicists. It broadly conveys that the quantum realm necessitates descriptions in terms of both particles and waves, and that the wave function, describing a quantum system, collapses upon interaction with an observer (who exists in the macro-physical world, somehow distinct from the quantum world). This narrative serves a rudimentary supporting role, primarily designed to avoid prematurely delving into complex interpretive details. Nevertheless, beneath this standard teaching narrative, the significant theoretical and interpretive commitments of physicists vary, largely depending on whether their work is predominantly theoretical or experimental.

Hence, a more pertinent counterfactual question might revolve around whether Bohmian mechanics could craft an equally effective teaching narrative, rather than questioning physicists' willingness to embrace the specifics of the Bohmian view over the interpretations offered by the Copenhagen group of physicists.

More importantly, given a general focus on theory in history and philosophy of physics, what any groundbreaking yet preliminary counterfactual account such as Soler's is likely to lack is an exploration of the rich experimental history of quantum physics. As I have argued in depth elsewhere (Perović 2021), this experimental work played a crucial role in guiding the development of quantum physics until the emergence of a coherent account of the microphysical world that would satisfy contemporary professional philosophers. In fact, the Copenhagen group was keenly aware of this pivotal moment when the topic of "interpretations," which greatly interests philosophers, became feasible.

For a more comprehensive perspective, it would be immensely valuable to investigate the potential alternative experimental paths and how they might have differed from the ones actually pursued. This exploration can provide insights into whether a different sequence of essential experimental contributions could have emerged with an alternative theoretical foundation, such as the Bohmian approach. It becomes essential to explore plausible counterfactual trajectories at the interface of quantum theory and experimentation. This approach may prove indispensable not only for counterfactual studies of quantum theory but also for the majority of key theories in physics and science in general.

Counterfactual Histories of the Theory-Experiment Interface

Instead of exclusively delving into the preliminary aspects of this particular case of counterfactual history related to the theory-experiment interface in quantum physics (as Soler herself used her case merely as an illustration for her larger point about counterfactual science studies), we will take a step back and pose more general questions. We aim to outline a comprehensive program for analyzing counterfactual scenarios in science, with quantum physics being an integral component, as we shall discover.

To begin, we must consider the relevance of counterfactual histories concerning the foundational experimental work and its connection to theory within the broader context of science. Specifically, how historically plastic has been the theory-experiment interface, and how does the extent of plasticity differ among various fields and cases?

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Another pertinent question is related to the positioning of inventions within the specific historical trajectories, both actual and counterfactual, driving the theory-experiment interface. Inventions exhibit varying degrees of dependence on the real-world theory-experiment interface. At times, they play a crucial role in shaping experimental apparatus and techniques, while in other instances, the theory-experiment interface itself prompts the emergence of inventions. A noteworthy example is the relationship between the steam engine and Thermodynamics. Sadi Carnot's (1897; originally published in 1824) theory of thermodynamic cycles, developed as a practical study of steam engines, is one such instance. However, it is conceivable that a more theoretical approach, akin to those formulated during the same period by Rudolf Clausius, Ludwig Boltzmann, and Josiah W. Gibbs could have taken precedence. How far back such an initial theoretical formulation could have been pushed is unclear without a meticulous case-study analysis of counterfactual scenarios. Moreover, it remains uncertain how early an applicable theoretical account similar to Carnot's style could have been inspired by a rudimentary steam engine that had already been constructed in Ancient Greece as a gadget.

So, how should we judge the plausibility of closely and less closely related possible worlds that might resemble actual science, and why is this distinction significant?
In the field of history of science, there are numerous captivating case studies and debates, especially concerning the role of inventions and scientific development during the industrial revolution (for an overview of a recent debate see the *Economist*: https://tinyurl.com/3vztkadz). These discussions often focus on 17th-century England and the factors contributing to developments during that relatively brief period, overlooking the long-term co-evolution that led to these developments throughout history. While this myopic approach is methodologically understandable as it helps identify critical factors within the episode, a more comprehensive perspective is essential.

When we take a broader view, the initial concern arises that what may appear as unlikely or imbalanced counterfactual historical trajectories to us, some placed even in the distant past, could have indeed been plausible scenarios at the time. Even the myopic episode of the so-called scientific and industrial revolution indicates that numerous alternative trajectories may have been rather obviously possible in the evolution of recent science.

Consider, for instance, the 19th-century fascination with building relatively impractical, stationary, giant telescopes, in contrast to later fully functional telescopes capable of tracking celestial movements. This clumsy and comparatively very limited approach involved substantial financial investments. Or, to venture further into the past, think of the Hven island project, which, by any measure, consumed an astonishing portion of Denmark's national GDP, with its assertive platinum-nosed owner playing a critical role in advancing Copernican science and observational studies in general.

Reflect on how long it took (around 350 years) to utilize the invention of lenses for constructing telescopes and pointing them toward the sky. Would such an episode have been deemed a plausible counterfactual story worth exploring at all, had people quickly realized they could fashion a telescope using two lenses? If these episodes had not transpired, and if e.g. financial resources and scientific interests had taken slightly different directions, all three scenarios might appear as counterfactual caricatures of history.

This leads us to question how far we should go in "caricaturing" history and what this may ultimately reveal about science and the history of the world itself.

The Meandering and Convergence of Historical Paths in Science and Its Applications

It is entirely conceivable that varying circumstances could have accelerated the practical applications of scientific knowledge by centuries or even millennia. Constructing plausible counterfactual scenarios of this nature is indeed enlightening in its own right. However, while the historical journey of science may exhibit significant and surprising flexibility, possibly spanning several millennia with various feasible deviations from actual trajectories, it is apparent that there is another key lesson to be learned from the study of science thus far: we've discovered that the joints at which science cuts up the natural world—to borrow a well-known adage—or junctures where science intersects with the natural world are not entirely arbitrary. Consider fundamental physical constants or the fact that we inhabit and observe the macro-physical world, not the micro-physical one. This macroscopic perspective ultimately led to the exploration of the ostensibly "peculiar" properties of the micro-physical world. It is challenging to envision how this historical scenario could have been reversed counterfactually (my guess is that it could not).

These junctures in nature may be understood differently within various theoretical and methodological frameworks, even in contemporary science (as exemplified in Soler's analysis), and thus may appear in somewhat contingent forms as interfaces between theory and experiment. However, the alternative historical space of these junctures has constraints that might escape notice when examining relatively brief time spans. If this is the case, then key milestones in the development of science are in the cards and are eventually grasped, either over the course of a couple of centuries or perhaps spanning thousands of years, but they are, nonetheless, reached. The plausible sets of potential theory-experiment interfaces, as they converge across various scientific domains, are necessitated by the fundamental joints of nature within a broader historical context. In the long term, these natural junctures channel potential historical trajectories in a specific direction.

The space of trajectories remains plastic—they could have diverged significantly from our actual reality—but there is a prevailing convergence. It is even plausible that the progress in biology might have surged ahead of physics, but the convergence between these disciplines would inevitably have started emerging at some point. The rapidity of this convergence (perhaps within a century or two, or more) is a topic for more in-depth analysis. Yet it is difficult to imagine advancements in fields such as molecular biology without the key progress made in physics (even if a trajectory of physics is treated as fairly far from our actual world) and the eventual synergy of chemistry with physics. Additionally, practical applications, as well as available experimental knowledge and techniques, would have naturally limited the possibilities of considerable separation of trajectories driving away one discipline from the over vast time spans (e.g. spanning millennia).

From Convergence in the History of Science to Convergence in the History of the World?

The perspective on the history of science that I briefly outlined stands in stark contrast to the Kuhnian model. It posits the existence of essential content within scientific knowledge and its continuity, albeit not in the simplistic form of "true theories" and "unique discoveries." The theory-experiment interface occupies a historically malleable space, but the fundamental principles of nature appear to guide it toward a broad convergence over an extended timeframe. The seemingly convoluted historical paths, both in substance and methodology, have led many philosophers to interpret the trajectory of science through anti-realist and, at times, anarchic lenses. This interpretation often arises from a failure to adopt a bird's-eye view of the overall history of science, informed by the nature of counterfactual paths.

The fundamental joints and junctures of nature necessitate specific tools too, and one of the inherent convergences of the theory-experiment interface is methodological. Thus, methodologically, we confront a wide domain at play in science, but different theoretical and experimental methods are also bound to eventually exhibit an underlying convergence. This arguably encompasses numerical and mathematical techniques, as well as experimentation. Indeed, the relatively unified methodology of science may be a pivotal reason why the counterfactual history of science serves as a more dependable analytical tool than the counterfactual history of world events alone. Counterfactual study of history, as a concerted method of analysis, remains sidelined in history as an academic discipline, primarily due to a lack of apparent payoffs. (For an interesting attempt to discuss and promote it see Ferguson 2008.)

In contrast to general history, the conclusions drawn from the counterfactual study of the history of science are likely to be more straightforward and conclusive in terms of comprehending the long-term development of science and drawing lessons for future developments and strategies. Furthermore, the counterfactual study of science can potentially provide a foundation and tangible motivation for the broader study of counterfactual history as I will argue in the concluding paragraphs.

It is essential to note, first, that historical scientific trajectories, as they meander through the physical, biological, and other fundamental junctures, inevitably converge one way or another. Inventions and scientific applications, instrumental in experiments and subsequently influencing larger society, co-evolve with the theory-experiment interface. They are intrinsically intertwined with the interface, even though they may extend its plasticity to some extent. Just consider the potential trajectories of inventions and theories such as the steam engine and Thermodynamics. Secondly, it's uncontroversial to claim that historical developments, in general, are significantly driven by these inventions and applications, as they provide key levers for new social relationships[1] and interactions with the environment. These catalysts manifest in various forms.

Think, for instance, of the 20th-century harnessing of electric power, which catalyzed the most productive economic revolution ever, stemming from a relatively brief and obscure study of electromagnetism. Consider the centuries-long incremental improvements in disease research and hygiene standards that culminated in the late 19th century. Contemplate how the atomic age and the internal combustion engine emerged from a lengthy trajectory of engineering-theory interface. (See Gordon 2017 for a remarkable account of the impact of these inventions on world economy, and rather tame impact of computers.) All of these advancements unquestionably transformed existing socio-economic relations and facilitated the creation of entirely new societal structures, commencing with the rise of multi-story buildings and the unprecedented pace of travel, with all the associated consequences.

Indoor plumbing, electric power, and internal combustion engines are either interdependent or even coextensive with the convergence points of theory-experiment interface trajectories, which may span millennia. While the order of theory, experiment, and inventions could have unfolded differently, perhaps in a scarcely recognizable sequence, given the convergence of the theory-experiment interface, they inherently tend to align societies in a general direction. Thus, it appears that there is a discernible direction in the course of world history, and perhaps the most promising avenue to explore the nature of this direction is through a counterfactual study of the history of science and its offshoots.

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[1] Whether these various ways of organizing society these are somehow in the cards or completely contingent is a whole other issue.