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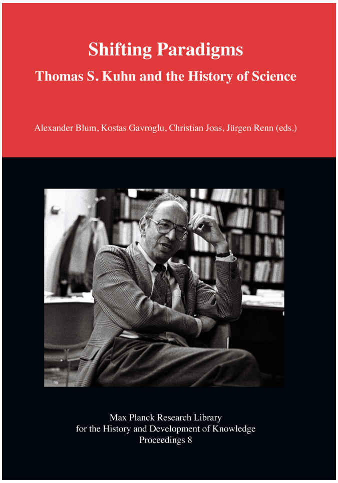

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Chapter 25
On Kuhnian and Hacking-Type Revolutions
Silvan S. Schweber

Since the mid-1970s we have been witnessing a deep structural change in the practice of the sciences, in the institutions that produce new scientific knowledge and new practitioners, and in the nature of that knowledge. And all these are at odds with the assumptions that underlay Kuhn's thesis in *Structure*.[1]

What happened in physics in the late 1970s was the culmination of the synthesis of quantum mechanics and the special theory of relativity into the quantum theory of fields. It resulted in the formulation of the "standard model of particle interactions" as the lowest level, context-free, description of the dynamics of the entities out of which the presently observable physical world is believed to be composed.[2] Furthermore, a justification was given for the representation of physical phenomena in quasi-independent atomic, nuclear and sub-nuclear levels. This hierarchical ordering goes far beyond the notion of the quantum ladder that Weisskopf had advanced in the early 1960s wherein each rung of the ladder is distinguished from its neighbors by the dramatic difference in the order of magnitude of the dimensions of the motions involved, and hence of the energy transfers involved in each of these levels (Weisskopf 1962).

Each of the present levels has been given a foundational theory—foundational, not fundamental—called an "effective field theory," the representation of the dynamics of the elementary entities out of which the more complex structures that populate the domain are composed.[3] Moreover, the relations between the effective field theories governing adjacent sublevels are calculable (Cao and Schweber 1993).

Each of the atomic, nuclear and sub-nuclear domains has been further subdivided by the amazing instrumental and theoretical advances of the past 50 years. These hierarchies are not considered independent, nor are they disconnected. There are highly accurate measurements of atomic energy levels that reveal nu-

[1] The present paper is based on joint work with Roly Belfer, "Hacking Scientific Revolutions," to be published.
[2] For a popular account see Weinberg (2013).
[3] Steven Weinberg is responsible for the extensive present day use of effective field theories. See Weinberg (1979, 1991, 1995–2000).

clear and sub-nuclear features. Similarly, the recent startling discovery of the necessity to assume the presence of cold dark matter—consisting of as yet undiscovered sub-nuclear entities—in order to make sense of new cosmological observational data is indicative of the linkage between the various levels. But these new observations have not destabilized the current amazingly accurate representations of the atomic world. And, needless to say, the linkage of these levels becomes explicit as soon as one tries to answer evolutionary questions.

Most importantly, to a *very high degree of precision*, advances in lower levels do not destabilize the effective field theory in any given level. Consequently, a degree of finalization has been achieved which implies that the aims of research in the physical sciences at the atomic, molecular, nano, meso and macro level are no longer the determinants of a fundamental theory, as was the previous aim of the sub-disciplines concerned with these realms. Instead it is the creation of novelty, the unraveling and conceptualization of the possible new structures that can emerge by composition or by the attainment of previously unreachable low temperatures and the representation of the dynamics, which are to describe the macro-systems and their relationship to lower level foundational theory.[4]

Furthermore, advances in computer hardware, software and memory devices have dramatically altered both experimental and theoretical physics. Kuhn was faulted for his emphasis on theory. One should now not only talk of experimental and theoretical physics, but in addition of computational physics. Computational complexity theory studies the intrinsic difficulty of problem-solving, that is, classifying which problems can be solved efficiently by computer and which cannot. Should there be a proof that claims problems exist that are significantly more difficult to solve than to verify a claimed solution, (i.e., the resolution of the P versus NP question, as claimed by the mathematician Avi Widgerson)[5] this should be considered a *law of nature*. This indicates the limits by virtue of the computational complexity of being able to compute the properties of the stable entities that populate a given level given the effective field theory of a more foundational one, and thus indicate limits of reconstructing the world from a foundational effective field theory without putting in additional empirical data.

[4]There is little question that a deep structural change has occurred. The explanation for the change has for the most part been concerned with political, economic and cultural factors, with less attention paid to cognitive factors internal to the various scientific and engineering disciples. The above suggests that cognitive factors are surely one of the reasons that the Bayh-Dole legislation has had such consequential impact on the restructuring of universities.
The Patent and Trademark Law Amendments Act (now known as the Bayh-Dole Act) was enacted by the US Congress in December 1980. The legislation gave American universities, small businesses and non-profit organizations exclusive patenting rights of inventions and control and property rights over intellectual materials that resulted from governmental funding. The legislation had been sponsored by senators Birch Bayh of Indiana and Bob Dole of Kansas.

[5]See, for example, Deutsch (2011).

Just as physics has been transformed, so has chemistry. Undoubtedly it is the biological and medical sciences that have been most deeply affected by internal developments: Crick and Watson, genetic codes, recombinant technologies, DNA-sequencing, genome projects, bioinformatics, CRISPR. It is in the biological and medical sciences that the entrepreneurial aspects of the university are most visible. My task as a historian of modern physics is to try to give an account of how the above outlined conceptualization of physics and the changes in its practices came about. The physics community would probably be satisfied with a *longue durée* narrative of the quantum "revolution," in which the notion of "revolution" and the contributions of the individuals believed to have been responsible for seminal, important advances are emphasized. When applied to physics, and more generally to science, "revolution" is a metaphor. Its political meaning implies the forceful, and at times sudden and / or unexpected, removal of a pervasive and dominating power, this in the name of an alternative, generalized view and ultimately offering a differing ordering of things.[6] As a metaphor in the history of science, "revolution" has been applied to describe the overthrow of a dominating tradition, as in the case of the "Einsteinian" general relativistic revolution, which overthrew the traditional "Newtonian" view of regarding space-time as a stage unaffected by the events occurring in it. Whether used metaphorically or otherwise, "revolutionary" developments in the sciences cannot be wrenched out of the contexts in which they take place and must be connected with the economy, culture, politics, institutions and so forth, of the societies in which they occur. This has been done for the "Scientific Revolution" by Schaffer, Shapin, Floris Cohen, Heilbron and others[7], by Ian Hacking[8] and others for the probabilistic "revolution," and is also being done for the quantum revolution.[9] My description of the quantum revolution emulates what Hacking did for the probabilistic revolution. Here I will only consider the "epistemological rupture" (Foucault 1976) aspects of the quantum revolution within the time frame 1900–1980.

The first point I wish to make is that the theoretical concerns and advances that culminated in the formulation of non-relativistic quantum mechanics by Heisenberg, Born, Jordan, Schrödinger, Dirac and Pauli in 1925–26 cannot be disconnected from matters of mathematics, chemistry, applied science, engineering and computing. Mathematics is a special language that makes objectivity

[6]This to differentiate a revolution from a *coup d'état*. It should be noted that even when a revolution fails it launches a long-term process of changes at every level.

[7]Cohen (2010); Heilbron (2013); Shapin (1996); Shapin and Schaffer (1985).

[8]Hacking (1987). See in that same volume the two other introductory essays: Cohen (1987) and Kuhn (1987).

[9]See for example Kragh (1999), and more recently Staley (2013).

and the unambiguous exchange of information. Furthermore, mathematics and physics have always been "co-constructed".[10]

A second point to be emphasized is that what was fundamentally new in Schrödinger's wave mechanics—in contrast to classical physics—is that the interacting entities participate as *objects*, whose structure, couplings and other attributes can change as a result of the interactions, and more particularly, that new *objects* can be formed. As important as were the calculations of Pauli and Schrödinger were in obtaining the level structure of the hydrogen atom—a new object formed by the interaction of an electron with a proton, or Heisenberg's explanation in explaining the level structure of the (two electron) helium atom, and the subsequent calculations to explain the periodic table, a further *crucial* calculation[11] was that of Heitler and London, which explained the formation of the hydrogen molecule.[12] By indicating how the charge density of the two electrons when in a singlet spin state lowered the energy by being locatable between the two protons, thus increasing the attractive forces between electrons and protons and shielding the repulsive force between the two protons, Heitler and London formulated the quantum mechanical basis for the covalent bond. The calculation gave a new quantitative perspective on bonding and saturation. In addition, the directional characteristics of orbitals when electrons were not in s-states were used to indicate how quantum mechanics could explain the bonding properties of the carbon atom, which was to understand the structure of organic compounds. A morphic element was thus introduced into quantum mechanical explanations (Gottfried and Weisskopf 1984–1986).

The quantum mechanical modeling of the atomic and nuclear world had two further attributes that were recognized early and shaped the approach to understanding phenomena at both the micro and macro levels:

1. A quantum description gives a measure of certainty to our knowledge of the world: it asserts that all hydrogen atoms in their ground state when isolated are identical; the same ist true for ^{23}Na atoms in their ground state. Similarly, that all lead $^{206}Pb_{82}$ nuclei in their ground state are identical[13]

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[10]This claim is expounded in the paper on which the present one is based. See Dear (1995); Gillies (1992) and therein Mehrtens (1992a and 1992b). For essentially a validation of the statement, see Krieger (2003), a remarkable, deeply insightful, historically sensitive study of mathematics and its relations to physics.

[11]I owe the notion of a crucial calculation to my colleague Howard Schnitzer at Brandeis.

[12]Heitler (1927). See Gavroglu and Simões (2012) for the details and subsequent developments.

[13]Upon receiving the 1993 Orsted medal for his contributions to the teaching of physics, Bethe in his acceptance speech stated "that there is a certainty principle in quantum theory and that the certainty principle is far more important for the world and us than the uncertainty principle. That doesn't say that the uncertainty principle is wrong. It says that the uncertainty principle just tells you that the

2. When computing the properties of atoms, molecules and solids, the value of the parameters that enter into the Schrödinger equation describing the dynamics of the system characterizing the electron and the nuclei—such as their mass, spin, magnetic moment, electric quadrupole moments—the values of these parameters are empirically determined. After the discovery of the neutron in 1932, and after models of nuclear structures had been advanced, these nuclear parameters were to be explained and their value quantitatively determined by the "lower level" theory that was to account for the structure and stability of nuclei (i.e by a description of nuclear dynamics in terms of neutrons and protons and the nuclear forces by which they interact).[14]

During the 1930s, many instances occurred that led to a novel conceptualization of physics began assuming an ever-greater importance. The quantum field theoretical demonstration that the electromagnetic interactions between charged particles could be explained as due to photon exchanges,[15] Fermi's formulation of a field theory of β-decay and Yukawa's suggestion that in analogy to electromagnetic forces the short range nuclear forces between nucleons could be generated by the exchanges between them of a hitherto unobserved massive particle were all examples of this. This novel conceptualization involved recognizing that, at the level of accuracy of possible physical measurements and the corresponding theoretical representations, the physical world could be considered *hierarchically ordered* into fairly well delineated realms and concerns: the macroscopic (consisting of solids, liquids, gases, their structure and their properties); the molecular and atomic realm; the nuclear; and the sub-nuclear ones and that the physical processes by which their connection is implemented could be given.

The atomic, nuclear and subnuclear realms became describable by separate (foundational) ontologies and corresponding quantum dynamics. The ontologies are connected to a given level—electrons and nuclei for the atomic and molecular realm and neutrons and protons for the nuclear level, with the latter's interactions at first described phenomenologically by nuclear potentials, and later assumed to be derivable from a quantum field theory of nucleons and mesons, once mesons were included in the basic ontology. The entities that comprised the foundational

concepts of classical physics, position, and velocity, are not applicable to atomic structure" Bethe (1993).

[14]It did so first in term of phenomenological internucleonic potentials. See Bethe (1937); Bethe and Bacher (1936); Livingston and Bethe (1937). [The above three lengthy articles comprise the "Bethe's Bible." They were republished as Bethe, Bacher and Livingston (1986).] Thereafter in attempts to determine these potentials on the basis of meson theories, and more recently in terms of the standard model. See Brown and Rechenberg (1996).

[15]See, for example, Fermi (1932).

ontology were considered the building blocks of the composite objects that populated that level.

The synthesis of quantum mechanics and special relativity resulted in the formulation of the quantum theory of fields. In the early 1930s, it predicted "antimatter." After the formulation of renormalization theory in the late 1940s, quantum electrodynamics gave a much more precise description of atoms. The formulation of non-Abelian gauge theories in the late 1960s to describe the weak interactions resulted in the unification of electromagnetism and the weak interactions, and provided the electroweak part of the standard model. Finally, the discovery of asymptotic freedom of non-Abelian gauge theories in the early 1970s completed the construction of the standard model, which encompasses most of the laws of physics known today.[16] But the inability to incorporate gravity into the standard model seems to indicate the limit of a quantum field theoretical description.[17]

What I have outlined is the thesis that the quantum "revolution" constitutes a Hacking-type (HT) scientific revolution[18], named after Ian Hacking who characterized the probabilistic revolution of the nineteenth century[19] in terms of the crucial novel feature of a scientific revolution: its *style of reasoning*.

Styles of reasoning are the constructs that specify what counts as scientific knowledge and constitute the cognitive conditions of the possibilities of science. They are made concrete through the specification of theories, their ontological assumptions and their explanatory models. A style of reasoning introduces new types of objects, evidence, sentences, (new ways of qualifying truth or falsehood), laws, modalities and most importantly, new possibilities.[20] Different styles of reasoning can coexist. Styles of reasoning are bound in scope with definite limits of applicability. But they are "big": they must encompass several scientific disciplines.

HT revolutions are considered emplacement revolutions, rather than replacement-revolutions. They change the way science is practiced without necessarily abandoning all the previous concepts by transforming it from within, through shifting the questions being asked and the criteria for acceptable answers, (these being a characteristic of an "emplacement revolution") (Humphreys 2011, 132).

[16] Wilzcek (1991), for a concise and authoritative overview of quantum field theory.

[17] Some physicists, e.g. Leonard Susskind, have suggested that the failure to synthesize quantum mechanics and *general* relativity has indicated the limits of the quantum mechanical description of physical nature. See Susskind and Lindesay (2005).

[18] Schweber and Waechters (2000); R. Belfer and S. S. Schweber, "Hacking Scientific Revolutions", to be published.

[19] Hacking (1987). See in that same volume the two other introductory essays: Cohen (1987) and Kuhn (1987).

[20] Hacking (1981a, 1981b, 1982, 1983 [reprinted 2002b], 1985, 1992a [reprinted 2002c], 1992b, 1996, 1994, 2002a, 2009, 2010 [reprinted 2011b]), *and especially* (2011a). See also Kusch (2010).

HT revolutions amalgamate pure and applied concerns. They transform a wide range of scientific practices and are multidisciplinary, with new institutions being formed that epitomize the new directions. These "new" institutions can however be "old" ones that have been restructured. The time scale of HT revolutions is the *longue durée*, but the *durées* have become shorter as the scientific community has increased. HT revolutions are linked with substantial social change, and after an HT revolution, there is a different feel to the world.

An HT revolution is characterized by a new style of scientific reasoning and conversely, the genesis of a new style of reasoning is indicative that an HT revolution is in the process of evolving, with self-authentication and self-stabilization that are characteristic features of the evolutionary process. Following Crombie (1994) Hacking gave the following examples of styles of reasoning: postulation in the mathematical sciences, ordering by comparison of variety and taxonomy, experimental exploration and measurement, the statistical analysis of populations and finally the derivation of genetic development.

HT scientific revolutions that are of particular interest have an additional feature: they make use of a characteristic *language* to formulate, corroborate, self-authenticate and self-stabilize the style of reasoning it introduced.[21] For the probabilistic revolution the statistical analysis of population regularities was its style of reasoning and the calculus of probabilities its language.

The style of scientific reasoning I associate with the HT quantum revolution is characterized by the hierarchization of the microscopic physical world and quantum field theory is its language.[22]

Considering a "big" scientific revolution such as the quantum revolution as a Hacking-type revolution allows for greater continuity with previous knowledge; it emphasizes the interdisciplinary aspect of the growth of knowledge and makes the social, sociological, cultural and the epistemological an integral part in the historical inquiry. It also considers the limits of the new knowledge and what it entails, which demarcates the revolution. Such a view challenges us to be better historians, yet recognizes the special character of being a historian of science.

[21] I do not wish to stretch the notion of language and associate with each Hacking revolution a language. But when relevant, I do place great emphasis on this notion of language.
[22] S. S. Schweber, "Hacking the Quantum Revolution," to be published.

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