Generating Ontology: From Quantum Mechanics to Quantum Field Theory

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Abstract

Philosophical interpretations of theories generally presuppose that a theory can be presented as a consistent mathematical formulation that is interpreted through models. Algebraic quantum field theory (AQFT) can fit this interpretative model. However, standard Lagrangian quantum field theory (LQFT), as well as quantum electrodynamics and nuclear physics, resists recasting along such formal lines. The difference has a distinct bearing on ontological issues. AQFT does not treat particle interactions or the standard model. This paper develops a framework and methodology for interpreting such informal theories as LQFT and the standard model. We begin by summarizing two minimal epistemological interpretation of non-relativistic quantum mechanics (NRQM): Bohrian semantics, which focuses on communicables; and quantum information theory, which focuses on the algebra of local observables. Schwinger's development of quantum field theory supplies a unique path from NRQM to QFT, where each step is conceptually anchored in local measurements. LQFT and the standard model rely on postulates that go beyond the limits set by AQFT and Schwinger's anabatic methodology. The particle ontology of the standard model is clarified by regarding the standard model as an informal modular theory with a limited range of validity.

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1 Introduction

This is the first of three articles on the significance of the epistemological/ontological circle for quantum mechanics and quantum field theory. This article will focus on the status of quantum mechanics and quantum field theory as *theories*. The second article will treat the relevance of advances in quantum physics for the interpretation of quantum mechanics. The final article will consider the significance a revised interpretation of physics has for some traditional philosophical questions that presuppose a more traditional interpretation. These are all offshoots of a forthcoming book.

Philosophical interpretations of physics have increasingly come to a focus on theories as the basic unit of interpretation. As van Fraassen (1991, p. 1) put it: “Philosophy of science has focused on theories as the main products of science, more or less in the way philosophy of art has focused on works of art, and philosophy of mathematics on arithmetic, analysis, abstract algebra, set theory, and so forth.” ‘Theory’, however, has various connotations ranging from the creationists’ put-down, ‘just a theory’, to particular theories, general theories, and abstract theories. We are concerned with the contrast between two accounts that can somewhat simplistically be labeled ‘formal’ and ‘informal’. Here, ‘formal’ refers to physical theories formulated, or rationally reconstructed, as a mathematical formulation that is given a physical interpretation. I will assume that this is familiar territory. This approach imposes constraints both on the formalism and on the method of interpretation. The basic constraint on the formalism is mathematical rigor. When mathematical formulations are treated as tools then many problematic mathematical issues, such as consistency, convergence, and scope of applicability, are effectively settled on physical grounds. Such physical justification is not acceptable when the mathematical formulation is treated as the *foundation* for an interpretation. This formulation must have a basic consistency independent of any physical interpretation.

The second constraint is that interpretation in the formal mode must be holistic, an interpretation of a theory as a unit. Here it is important to distinguish particular theories, e.g. of ferromagnetism, superconductivity, etc., from foundational theories. In philosophical reconstructions the latter generally function as units in three different contexts. They are units of explanation, our primary concern. They are also evolutionary units. Conceptual revolutions are interpreted as the replacement of one theory by a successor. Finally, they supply the basis for settling ontological issues. Interpretation, according to the semantic method, is a model-mediated relation between a theory and the things it is a theory of.

This stress on formal theories as basic units of interpretation has come under criticism. Cartwright (1983) contends that phenomenological theories have more ontological significance that foundational theories. Giere (1988, Chap. 3) argues that interpretations based on rational reconstruction of theories tend to be question-begging. Morgan and Morrison (1999, Introduction) show that the models that play a basic role in scientific explanations are generally not the models of theories that are basic to interpretation in the semantic model. I would stress two further criticisms. First, there is almost no historical warrant for the claim that formal theories supply a basis for settling ontological questions generated by theories. The link between theories and ontology was originally given by Sellars, Quine, Maxwell, and others as a way around the positivist rejection of theoretical entities. Many philosophers, myself included (MacKinnon, 1972) bought the claim that having good reasons for accepting a theory as fundamental and irreducible entails having good reasons (essentially the same reasons) for accepting the entities posited by theory. Historically, the formalization of a functioning theory has played a negative role in deflating ontological claims. Newton (3rd Rule of Reasoning) insisted that hard massy corpuscles have a foundational role in mechanics. Lagrange's formulation dispensed with such ontological foundations and made mechanics a branch of analysis. Maxwell kept insisting on the reality of displacement as a basis for electrodynamics, in spite of the objections of Thomson and distance theorists. Hertz's contention that Maxwell's theory is Maxwell's set of equations, set the classical formulation of classical electrodynamics. Positive contributions are exceptional and debatable. The best-developed case is Friedman's argument for the reality of the space-time manifold based on a semantic reconstruction of space-time theories. Reconstructions of non- relativistic quantum mechanics will be considered in the second article.

The second difficulty is that a following of this methodology in settling ontological issues effectively excludes the theories that have had the greatest success in giving depth level accounts of physical reality: relativistic quantum mechanics (RQM); quantum electrodynamics (QED); nuclear physics; Lagrangian quantum field theory; and the standard model of particle physics. A couple of examples will illustrate the problematic we will consider. The RQM stemming from Dirac's 1928 paper never achieved the status of an independent theory. Early reactions to Dirac's theory were characterized by two terms, 'magic' and 'sickness' (Moyer, 1981b, 1056): magic in yielding spin, spin-orbit interaction, and other properties of electronic interactions on the basis of formal considerations that most found unintelligible; sickness in yielding puzzling negative energy solutions and in not conforming to standard modes of interpretation. Eventually, the Dirac solution was reinterpreted as a one- particle fermion wave function, that could be second-quantized. In spite of such formal difficulties RQM can be considered a theory in the loose sense common in physics. It is effectively a fusion of two principles, QM and relativity. As such, it supplies a secure basis for ontological claims and predictions. Whenever a new fermion is discovered there must be a corresponding anti-of particle. Something similar obtains in phenomenological quantum field theory. Gell-Mann's 8-fold way not only led to the prediction of the Ω^- particle with an isospin value of -2, a strangeness of -3, and a mass of 1675 Mev. It also supplied detailed guidance for the experimental search. When the bottom quark was discovered, physicists concluded that there had to be a top quark and eventually found it. This functional ontology did not follow as an ontic commitment of a formal theory, but as a consequence of the application of the principles group theory.

The exclusion of these theories from philosophical debates about the ontology of physics is not a choice based on whim, preference, or prejudice. It is rooted in a methodology of interpretation and its presuppositions. The methodology has been sketched. The presupposition is that mature theories can, as a matter of principle, be recast as interpretable theories. QED and the standard model are mature theories. There is no reasonable expectation that they can ever be recast in accord with the norms proper to a formal theory. QED remains an ugly, but surprisingly successful, set of rules. What must be done, accordingly, is to find a way of relating philosophical questions about epistemology and ontology to functioning physical theories, rather than idealized reconstructions. Before undertaking this quest in QFT we should list some characteristic features of informal theories that distinguish them from formal theories.

First, many informal theories, including all the theories we will be considering are modular constructions.[1]. The different modules assembled include QM, relativity, group theory, symmetry principles, and local gauge invariance. Second, an informal theory is never an uninterpreted formalism. Many of the modules have physical interpretations prior to their incorporation in a new theory. An effective theory, a topic we will treat later, relies on parameters that are accepted as factual claims with the hope that they might be explained by a deeper level physics. Third, consistency requirements are not those proper to a formal theory. The effective consistency requirements emerge from a fusion of physical and mathematical considerations. QED illustrates the difference. It does not have a proper mathematical consistency. The series expansions used have never been shown to be Cauchy convergent, and probably do not converge. Yet, this is considered a *physically* consistent theory. Because of regularization and renormalization results can be calculated to any desired degree of accuracy. Fourth, the mathematics used is often treated as a tool, rather than a formal system. This involves relying on physical reasons for justifying the use and scope of much of the mathematics. The old slogan is: Too much rigor leads to *rigor mortis*. Fifth, ontology is functional. The interpretation of a theory does not involve a comparison of what the theory says with reality, as it exists objectively. It involves relating conclusions deduced from the theory with reality as reported by experimenters. Finally, the context for interpretation is the ongoing dialog between theoreticians and experimenters. This necessitates a serious consideration of the role of language in interpreting theories. In both the syntactic and semantic models of theory interpretation the role of language is not a component in the methodology of interpretation.

The role of language in the interpretation of physics is the background theme of these articles and the central topic of the forthcoming book.[2] For present purposes I will mention two points that characterize a basic difference in the consistency requirements proper to the formal and informal senses of 'theory'. Particle physics developed through extremely close collaboration between experimenters and theoreticians. Until the mid-1970's experimental physics led the advance through repeated discoveries of particles and resonance states that theoreticians attempted to explain. Since then theoreticians have dominated the advance wave guiding experimental research for the unique events predicted by theories.[3] We can bring out a basic consistency problem by focusing on the use of 'particle'. Experimental research centers on particle collisions and the resulting debris. Experimental 'particles' are usually not identical with theoretical 'particles'. Many field theorists think of 'particle' as a phenomenological concept to be explained in terms of more basic fields. An observed particle is often a superposition of particles more basic in theory. Finally, detected particles are clothed particles, rather than the bare particles basic to particle theories. The theoretical usage of 'particle' must be developed in a way that can accommodate both mathematical formulations and experimental testing.

This leads to the second consideration. Informal inferences play an indispensable role in experimental research. Here the use of ‘formal’ and ‘informal’ parallels their usage in discussing theories. Formal inferences are in accord with rules whose validity is independent of the content to which they are applied. Informal rules depend on the meanings of terms and the conceptual entailments they support. To illustrate the role of informal inferences in experimental analysis we will consider the experiment by Lamb and Retherford that spearheaded the experimental advances we are considering. (Lamb and Retherford, 1947; reproduced in Schwinger, 1958, pp. 136-38)

Lamb and Retherford heated hydrogen molecules in a tungsten oven that separated the molecules into their atomic components. They bombarded the emerging atoms with electrons and then with microwave radiation. Both processes were carried on in a magnetic field. Then they recorded the currents when the atoms moved to a metal surface connected to a current amplifier. This is a descriptive account. The interpretation accorded it depended on a nested series of inferences. They inferred that the oven heat dissociated hydrogen molecules into hydrogen atoms, that electron bombardment raised some of these atoms to the $2S_{1/2}$ state, that atoms in this excited state were metastable and could decay by ejecting electrons from a metal target, and that these electrons produce the observed current. These routine inferences supplied the background for the crucial inference that microwave radiation of the right wavelength would cause a transition from the $2S_{1/2}$ state to the $2P_{1/2}$ state. This, in turn supported the further inference that the atoms in the $2P_{1/2}$ would not cause electron emission when they hit the metal target. Atoms in this state would decay almost immediately to the $1S_{1/2}$ state. Hence, the difference in current between runs with and without microwave radiation would serve as a measure of the transition from the $2S_{1/2}$ to the $2P_{1/2}$ states. These were the principal inferences. There were further inferences concerning the Zeeman splitting caused by the magnetic field, the changes this produces in energy levels, the increased frequencies of microwave radiation needed to accommodate these increases, and extrapolations from strong to zero magnetic fields. These experimental inferences presupposes a loose informal unification that allows and interrelates inferences based on thermodynamics, electronics, atomic physics, electrodynamics, as well as methods of inference developed in experimental traditions.

2 A Minimal Basis

To consider the ontology resulting from extensions of quantum mechanics we should begin with a minimalist perspective that does not presuppose an ontological interpretation of QM. This also admits of a formal and informal version. We will consider both to see the role each plays in interpreting the extensions of QM. To clarify what is meant by a minimal basis for settling ontological claims, we should consider the notion of an *epistemological circle.*[4]I will focus on the significance this has for the conceptual core of the language used to communicate information.

Consider the functional epistemological/ontological distinction on the most basic level, aka lived world semantics or common sense realism. The implicit ontology, or descriptive metaphysics, of ordinary language, centers on a subject/object distinction and a representation of reality as a collection of interrelated spatio-temporal objects with distinctive properties and activities. The implicit epistemology presupposes a subject as a passive receptor. We normally perceive objects and events as they exist objectively. This is not presented, or defended, as a philosophical theory. It is generally implicit and functional in the sense that normal human interactions presuppose that we perceive things as they exist objectively unless there is a specific reason for doubt. We absorb this by, among other things, learning how to use such related terms as ‘look’ and ‘see’, ‘listen’ and ‘hear’, ‘reality’ and ’illusion’. Routine communication presupposes this basic consistency between objective reality and our cognitional apparatus. The language of classical physics preserved and streamlined the conceptual core of ordinary language. The basic epistemological circle of classical physics presupposes an ontology of objects and fields, both possessing quantitative properties. The knowing subject is a detached observer, someone capable of recording objective reality without necessarily modifying it by the act of knowing. Experimentation presupposes that instruments are also explained in terms of objects and fields. Again, it should be stressed that this is not being presented as a philosophical theory. It is simply a clarification of presuppositions implicit and functional in normal discourse.

The symbiotic co-evolution of physics and mathematics led to a fundamental consistency between basic concepts of physical reality and the way they are expressed mathematically. I will first present the mathematical expression of this conceptual core and then consider its breakdown. The basic relation between the mathematical representation of space, time and objects was first elaborated in a relativistic context and later adapted to non-relativistic physics (Levy- Leblond, 1963. See also Castellani, 1998.) We will begin with a descriptive account of the non-relativistic formulation and then summarize the mathematical formulation of the relativistic account. This is actually simpler than the non- relativistic account and more pertinent to the material we will be covering.

Galileo gave conceptual arguments for his principle of inertia, a principle needed to defend the idea of a moving rotating earth. A person inside the cabin of a ship moving smoothly in a straight line sees dropped objects fall vertically and insects or birds flying equally well in all directions. The laws of physics are invariant with respect to uniform local motion. This can be expressed more formally in terms of the Galilei group,

$$G = (b, \mathbf{a}, \mathbf{v}, \mathbf{R}), \tag{1}$$

where b is a time translation, $\mathbf{a}$ is a space translation, $\mathbf{v}$ a boost, or a change from one velocity to another, and $\mathbf{R}$ is a rotation. Thus, a transformation,

$$\mathbf{x}' = \mathbf{R}\mathbf{x} + \mathbf{v}t + \mathbf{a}, \tag{2}$$

leaves the system unchanged.[5] For this to be a group there must be an identity element, $(1) = (0, 0, 0, 1)$. The product of any two elements must be a member of the group, and every element must have an inverse. Working out multiplication, inverses, subgroups, and irreducible representations for the Galilei group is more complex and less insightful than for the relativistic Poincaré group, which we will now consider.

The Poincaré group is a composite of two groups, the group of proper Lorentz transformations, which excludes inverses, and the group of displacements. The relativistic equation generalizing eq. (2) for the transformation from an inertial system, S to another inertial system, S' is

$$x'_\mu \;=\; \Lambda^\mu_\nu \, x^\nu \;+\; a^\mu, \tag{3}$$

where Λ^μ_ν represents the homogeneous Lorentz group a^μ is the displacement, Greek superscripts represent 4-dimensional contravariant vectors ($x^0 = ct, x^1 = x, x^2 = y, x^3 = z$), and there is a summation over repeated indices. Using the metric tensor,

$$g_{\mu\nu} \;=\; \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \tag{4}$$

Contravariant and covariant vectors transform as $x_\mu \;=\; g_{\mu\nu}x^\nu$. For motion along the x^1-axis

$$\Lambda^\mu_\nu \;=\; \begin{pmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad \text{where } \gamma \;=\; \frac{1}{\sqrt{1-\beta^2}},\; \beta \;=\; \frac{v}{c}. \tag{5}$$

What Wigner showed in his classical article is that basic properties of particles, or systems whose internal configurations are not considered, can be deduced from relativistic invariance.[6]. Two cases must be distinguished. A particle with rest mass will have an intrinsic angular momentum, J, or spin, S for an elementary particle. Particles with zero rest mass move with the speed of light and can have only two directions of polarization. Since the Poincaré group contains subgroups isomorphic to the 3-dimensional rotation and displacement groups it seems reasonable to suppose that the Galilei group should lead to the same conclusion for particles with rest mass. However, as Levy-Leblond has shown, the group properties of the Galilei group are more complicated. Instead of the Galilei group one needs the covering group to conclude that irreducible representations correspond to particles of fixed mass and angular momentum.

An elementary system is characterized by spatio-temporal position, rest mass, momentum, and spin. A mathematical representation of these quantities requires some process of measurement as a means of attaching numbers to quantities. A basic requirement for consistent measurements is that there be a homomorphism between a conceptual relational structure and a mathematical relational structure (See Krantz et al, 1971). We will indicate how this is developed for the quantities that represent the core properties of bodies. A system, Υ is represented by a point in phase space (classical) or a vector in Hilbert space (quantum). Changes in the system are represented by canonical transformations (classical) or unitary transformations (quantum). Since, in our minimalist methodology, we are not yet distinguishing the two, we will let each operation be represented by an operator, U. Then we should consider how a U transformation in function space is related to the spatio-temporal representations covered by the Poincaré group. To begin on the simplest level, consider a one-parameter change in the spatio-temporal representation, e. g., motion in one direction or rotation about one axis. This induces a change from one state-space (phase or Hilbert) representation of the system to a different state-space representation. The generalization of this is that a Lorentz transformation induces an automorphism in the state-space representation. We will only consider continuous transformations, nor reflections. We need the properties of U in

$$\Upsilon' = U[\Lambda, \mathbf{a}]\,\Upsilon. \tag{6}$$

Consider an infinitesimal homogeneous transformation close to the identity. Then eq. (3) takes the form,

$$\begin{aligned} x'^{\mu} &= x^{\mu} + \omega_{\mu\nu}\, x^{\nu} \\ &= (\delta_{\mu\nu} + \omega_{\mu\nu})\, x^{\nu}, \end{aligned} \tag{7}$$

where $\delta_{\mu\nu} = 1$, if $\mu = \nu$; 0 otherwise. $\omega_{\mu\nu}$ is an infinitesimal. To evaluate it we consider another event, $\bar{x}$ and the same infinitesimal transformation to get

$$\begin{aligned} x^{\mu}\bar{x}^{\mu} &= (x^{\mu} + \omega_{\mu\nu}x^{\nu})(\bar{x}^{\mu} + \omega_{\mu\nu}\bar{x}^{\nu}) \\ &= x^{\mu}\bar{x}^{\mu} + x^{\mu}\omega_{\mu\nu}\bar{x}^{\nu} + \bar{x}_{\nu}\omega_{\nu\mu}x^{\mu}, \end{aligned}$$

leading to $\omega_{\mu\nu} = -\omega_{\nu\mu}$. We can use this in an infinitesimal expansion of U to get

$$U[1 + \omega, \epsilon] = 1 + (1/2)\omega^{\mu\nu}J_{\mu\nu} - i\epsilon^{\mu}P_{\mu}. \tag{8}$$

$J_{\mu\nu}$ may be identified with the standard angular momentum components and P_{μ} with the 4-momentum.

We may summarize the significance of these conclusions for our minimalist approach. The core of the extended ordinary language proper to physics is a reductionist conception of physical bodies as composites of particles. In this context 'particle' means a system whose internal structure, if such there be, is not considered. This external specification of a system accords mass particles the basic mechanical properties of position in space and time, relative to a measuring apparatus that anchors such measurements, 4-momentum, or momentum and energy, and angular momentum, or spin. These measurements, made in the observer's rest frame presuppose rigid rods, or a technological substitute, to measure length, and regular (clock-work) processes to measure time. These are treated as classical measuring devices or standards. This fits the treatment of space, time, and bodies in special relativity. It also accords with the representation of systems by points in phase space or vectors in Hilbert space.

In a quantum context, this classical epistemological circle breaks down when considering certain types of *paired* experimental frameworks. This breakdown concerns informal inferences, rather than mathematical representations. Material inferences must be restricted to particular experimental frameworks, rather than the unrestricted applicability characterizing classical physics.[7] The normal epistemological circle does not support material inferences from one framework to another. Two differing experimental frameworks can be related by mathematical formulations. However, this unifying mathematical formulation does not support a standard ontological interpretation. An analysis of the epistemological circle and its breakdown in a quantum context requires some consideration of a dual inference system. One, an informal system, supports the normal practices of experimental inference. In practice this is rarely treated, or even recognized, as an inference system. It is simply treated as a recognition of the normal properties and activities of objects and instruments. It generally emerges into conscious awareness as an inference system only when it breaks down.

This problematic situation was recognized, but not clarified, prior to the development of quantum mechanics. Thus, X-ray researchers studying the sources of radiation presupposed a wave (or field) framework and inferred that the intensity of the radiation is proportional to the inverse square of the distance from the source. Experimenters studying the detection of X-rays found intensities much greater than predicted and came to rely on inferences based on particle trajectories. The theories then available did not supply a basis for interrelating these different experimental frameworks. The underlying problematic was originally framed in ontological terms. How can something possess both wave and particle properties? Bohr transformed this from an ontological to an epistemological problematic.

2.1 Bohrian semantics

After Bohm developed his hidden variable interpretation, quantum mechanics could be considered a mathematical formulation that admitted of different physical interpretations. Heisenberg vigorously defended the Copenhagen interpretation, effectively transforming rules for the practice of physics into the interpretation of a theory.[8] Bohr never presented his position as the interpretation of a theory, but as a clarification of necessary conditions for the unambiguous communication of information concerning atomic systems, particles and their interactions. This semantics is our concern.

Any presentation of Bohrian semantics involves a tangled complex of interrelated exegetical, philosophical, and scientific problems. These cannot be untangled here. I will simply supply enough background to understand the semantic transformation Bohr sought to achieve and indicate sources where these issues are treated in more detail. Since his undergraduate days Bohr had an abiding concern with the epistemological problems involved in interrelating cognition, language, and observation. Like Wittgenstein, he kept going over and over the same basic issues until he achieved a position he thought coherent and adequate. Neither he nor Wittgenstein referred to or relied on standard philosophical sources. The language in which Bohr formulated these problems was shaped by the tradition of *Erkenntnistheorie*, a tradition that centered on the problem of adapting the Kantian legacy to advances in knowledge. Physics became philosophically problematic for Bohr only with the breakdown and reinterpretation of the Bohr-Sommerfeld program. Bohr's position entered the Anglo-American philosophy of science arena warped by three distorting factors. First, the empirical tradition used the same basic terms as the Kantian tradition, but embedded them in a quite different conceptual framework. Second Bohr's position was identified with the Copenhagen interpretation of quantum mechanics as a theory. The third distorting factor, it must be admitted, is Bohr's involuted, dialectical style of presentation, a style that almost guarantees misinterpretation.[9]

Here I am not trying to present a general account of Bohr's position, but simply to clarify his transformation of the semantics of classical concepts. Other physicists viewed the contradictions and paradoxes generated by the the new quantum physics in ontological terms. How can electrons have both wave and particle properties? How can X-rays propagate from a source in a spherical fashion and then strike only at a point? Around 1924 Bohr experienced something of a *Gestalt* shift from an ontological to an epistemological perspective. His concern shifted from the properties of objects to the use of 'object'. Instead of asking what properties particles *possess* he began to ask what properties can be attributed to electrons. This effect was somewhat similar to the epoché advocated by Husserl. He stressed the need for philosophers to bracket the natural standpoint and consider the representational system, rather than the reality represented. Similarly, Bohr's realization of the essential failure of the pictures in space and time on which the description of natural phenomena have hitherto been based shifted the focus of attention from the phenomena represented to the system that served as a vehicle of representation. This epistemological shift permeated the famous Copenhagen discussions where Bohr, Heisenberg, Pauli, and Schrödinger shaped the interpretation of the new breakthroughs in quantum and wave mechanics. After the basic modifications in the use of physical terms was incorporated into the normal practice of physics, the linguistic crisis that precipitated the changes receded into the collective unconscious of the physics community. To understand the *Gestalt* shift it helps to retrieve the crisis that precipitated it. What follows is a summary of a more detailed presentation given elsewhere.[10]

The Bohr-Sommerfeld model of the atom relied on electrons traveling in elliptical orbits characterized by quantum numbers. The quantum numbers n and k ($k = l + 1$ in current usage) represented an electron's orbit and ellipticity. The new numbers, j and m that Sommerfeld had introduced to characterize spectral lines were gradually transferred to orbital electrons, though their precise significance remained a matter of debate. In the face of increasing difficulties Bohr began to reexamine the role of concepts in the interrelation of descriptive and scientific accounts. Thus, in his Nobel prize address he claimed: "We are therefore obliged to be modest in our demands and content ourselves with concepts which are formal in the sense that they do not provide a visual picture of the sort one is accustomed to require of the explanations with which natural philosophy deals." (Bohr: Collected Works, Vol. 3, p. 342). In his original use of the 'formal/descriptive' distinction, descriptive accounts, including those relying on quantum numbers functioned independent of theories. His insistency on an overall consistency led to a rejection of Einstein's light quantum hypothesis.

As a reliance on a realistic interpretation of descriptive accounts, especially of electronic orbits, increasingly generated contradictions, Bohr came more and more to rely on concepts that are formal, in his sense of the term. By the time he developed his account of the periodic table only the k quantum number was accorded a realistic interpretation. He still rejected the light quantum hypothesis on the grounds that a wave picture was needed to describe the propagation of electromagnetic vibrations in space. Three subsequent developments undermined these descriptive props. Compton's paper on the scattering of X-rays from electrons strongly supported the light quantum hypothesis. The reinterpretation of Bohr's account of the periodic table by Stoner and others was purely formal in that it relied exclusively on quantum numbers, rather than any descriptive accounts of orbits. Pauli extended this through his criticism of descriptive accounts of electronic motions and his exclusion principle, based exclusively on the assignment of quantum numbers. Bohr's last ditch defense of his older views was given in the famous (or infamous)1924 Bohr-Kramers-Slater paper.

The strategic idea behind the BKS theory was to find some way of harmonizing the continuity of classical electrodynamics, required to explain the interference effects optical instruments exploited, and quantum discontinuity. Statistically state transitions in a collection of atoms are equivalent to the harmonic components of a collection of virtual oscillators with frequencies corresponding to energy differences. No way had ever been found to explain continuous vibrations through state transitions. Virtual oscillators fit a spatio-temporal description of radiation into a quantum account of the production of radiation. No alternative account did this. Hence Bohr and Kramers, but not Slater, dropped the assumption of light-quanta and assumed that stationary states communicate by a spatio-temporal mechanism that is virtually equivalent to the radiation field. Einstein had argued from momentum conservation to light-quanta with momentum hc. A denial of light-quanta reversed Einstein's argument and led to the non- conservation of energy and momentum. In this framework Bohr's Correspondence Principle (CP) achieved a new significance. The new usage abandoned any reliance on spatio-temporal descriptions of electronic orbits and relied on damped simple harmonic oscillators providing all the allowed frequencies.

The BKS paper soon succumbed to internal criticism and experimental refutation. Bohr saw this refutation as a conceptual advance. In a talk given in August 1925, before he was familiar with Heisenberg's paper originating quantum mechanics, Bohr claimed

> From these results [the Compton effect and the Bothe-Geiger experiment establishing energy and momentum conservation for individual interactions] it seems to follow that, in the general problems of the quantum theory, one is faced not with a modification of the mechanical and electrodynamical theories describable in terms of the usual physical concepts, but with an essential failure of the pictures in space and time on which the description of natural phenomena has hitherto been based.

The term 'picture' functions in the neo-Kantian context of concepts that make external representations possible. Thus 'particle' functions as the center of a cluster of concepts needed to describe natural phenomena. A classical particle is an object whose structure, if such there be, is irrelevant in the context. A particle travels in a trajectory, collides with other objects which it may penetrate, be deflected by, or recoil from. In our terminology, adapted from Wilfrid Sellars, this cluster of concepts supports material inferences that play an indispensable role in interpreting experiments and reporting results. Similarly 'wave' is at the center of a different conceptual cluster. The meanings of these terms are determined by their usage in classical physics, where they also have a clear referential function.

The extension of these classical terms to a quantum context introduces a tension in the epistemological/ontological circle. The classical meanings presuppose a classical ontology, an implicit understanding of what particles and waves are and do. The use of these terms in a quantum context cannot have the same ontological significance. Speaking of electrons as either waves or particles in a context-free fashion generates familiar contradictions. Yet one cannot interpret experimental results while dispensing with such terms or giving them new quantum meanings. How are such concepts to be understood?

Bohr gradually answered such questions by a kind of pincer action. The lower pincer gripped thought experiments: idealized measurements of position or momentum; the single/double slit experiment, the γ-ray microscope; a box with a trapped photon suspended by a spring. The top pincer came to grips with the functioning of concepts. Here Bohr's basic conceptual tool was his *correspondence principle*. Today, this is used almost exclusively in the form of the backwards CP: Quantum formulations reduce to classical formulations in the limit where $\hbar \to 0$ or $n \to \infty$. Bohr and his associates focused on the forward CP, using classical formulations as a springboard to leap to quantum formulations. In the late 1920's his treatment of concepts, as Chevalley analyzed it, went through four stages. The first two, formal analogies and symbolic analogies, were probably conditioned by ideas derived from Kant's Critique of Judgment. Though it is unlikely that Bohr ever read this work, he was familiar with Goethe's adaptation of it, the idea that analogies transfer a structure from pictures, while loosening the dependence on intuition (*Anschaulichkeit*). The third stage stressed a necessary ambiguity, stemming from his gloss on the uncertainty principle. The final state is the more familiar notion of complementarily. Bohr's views continued to develop to meet the challenges presented by RQM , nuclear physics and QED[11] His final stage, around 1937, culminated in his use of 'phenomenon' as a special unit, including the system studied and the experimental apparatus used. This was considered a minimal unit in which problematic terms could be meaningfully used. Since this is a potentially misleading use of 'phenomenon' I will substitute 'framework'.

With this background and a couple of disclaimers we may summarize Bohrian semantics in a set of basic claims. The first disclaimer is that this is not presented as a definitive account of Bohr's position, but as a position supported by an analysis of the use of language in physics. I believe that it is faithful to Bohr's position, but do not want to be wander any further through the warren of Bohrian exegesis. Second, this is not an interpretation of QM. It is a minimal epistemological position that serves as a point of departure.

1. The goal of Bohrian semantics is one of preserving the conditions necessary for the unambiguous communication of information between experimenters and theoreticians. It is not the interpretation of a theory.

2. Ordinary language supplies the general framework for intercommunication. The dialect of *physicalese* developed through the co-evolution of the language of physics, the mathematics that expresses it, and the experimental methods that stimulate and support it. The conceptual core of physicalese still embodies the functional ontology or ordinary language: a fundamental subject/object distinction, and spatio-temporal objects with properties and causal connections.

3. The classical meanings of core terms is set by their usage in classical physics (something broader and more informal than classical mechanics)[12]. New terms, e.g. 'nucleon', 'meson', 'quark', can be added. However, any analysis of collision experiments involving such new additions still relies on the material inferences linking trajectories, collisions, etc., supported by the classical concepts.

4. Classical ontology does not carry over to the quantum realm. Here 'classical ontology' refers to the basic ontology implicit and functional in the language of classical physics. Here the subject/object distinction takes the historically conditioned form of an independent observer confronting a world whose objects, properties, and interactions are independent of the observer's knowledge. Categorial terms supporting referential usages have an unrestricted validity.

5. A measurement supplies the minimal framework in which classical terms can be used unambiguously in quantum contexts. The term 'measurement' has acquired a connotation broad enough to include thought experiments. This usage does not presuppose or support meanings set by reference. Meanings are set by classical usage. Attempts to extend this usage beyond the experimental framework of a measurement can generate contradictions.

2.2 Quantum Information Theory and the Foundations of Quantum Mechanics

Quantum information theory (QIT) emerged from a science-fiction status in 1994 when Shor used QIT to develop an algorithm for factoring large composite numbers. QIT has a potential for relating to quantum computing, cryptography, teleportation, and the foundations of quantum mechanics. Its present status is somewhat paradoxical. As any internet search will reveal, publications on this topic are growing at an exponential rate. Yet, actual achievements are sharply limited. Quantum computers, quantum cryptography, and teleportation are not expected in the immediate future.[13] We will only consider the bearing of QIT on the foundations of quantum mechanics and will focus on one limited issue, the relation between epistemological and ontological interpretations. In principle the relation of QIT to the foundational problem is simple. The question, "Why quantum mechanics?" can be answered: "Because QIT postulates yield quantum mechanics." Since the foundation is information, QM should be interpreted as a theory about information, not micro-particles. This, accordingly, is an epistemological, rather than an ontological, interpretation. However, both the question and the response rest on layered supports that invite closer consideration.

Using QIT to answer the Why QM question involves putting the classical/quantum transition in a new perspective. A bit of background information may be helpful. Before considering the significance of *quantum* information theory, we should note the bearing that information theory in general has on some of the issues we have been considering. First, it supports a shift from an ontological to an epistemological perspective. Consider planning a long car trip by getting maps, planning routes, getting information on traffic, road conditions, speed limits, and travel amenities. We might digitize the route by representing each intersection by a 6-bit matrix, with 4 bits to accommodate the type of intersection (one turn, two turns, cloverleaf, overpass) and 2 to represent the choice of turn and direction. Then all the pertinent information is a sequence of $1's$ and $0's$. When one studies programs and algorithms, rather than streets and maps, the ontology tends to evaporate. If similar algorithms can cover road trips, warehouse storage, dentist's records, and baseball schedules, then the content is bracketed. If information can be stored on tapes, CD's, chips, electromagnetic vibrations, or printed pages, then we focus on the information rather than on the material substratum.

Information theory generally treats events, rather than objects as such. It also minimizes the significance of a space-time background as a framework. Suppose that Alice communicates with her fellow spy, Bob, through a 1-bit signal. Then information is sharply localized, and is open to easy detection. But, suppose Alice and Bob each send 1-bit units to their agent, Charlie, while Dave, the spy master, sends Charlie a 1-bit signal indicating the actions to be taken if Alice and Bob's bits agree or disagree. For security reasons signal sending varies from e-mail, to regular mail, to classified ads, to carrier pigeons. The decisive information is relational and only admits of a very general localization.[14]

There are two further considerations that have a bearing on the epistemological circle of QIT. The first concerns measurement. The application of QIT to the foundations of QM presupposes an entangled system. Someone is supposed to measure a part of the system, dubbed the ancilla, and then attempt to infer corresponding values for the unmeasured part. A subsystem is represented by a partial density matrix, not a vector. Measurements do not yield eigenvalues of the system. One needs the notion of a positive operator valued measurement (POVM).[15] The second point concerns the switch from geometric to algebraic representations. A system in a state is represented by a point in phase space (classical) or by a vector in a Hilbert space (quantum). These are geometrical notions with an ontological significance. Within the appropriate epistemological circle they are intended as representations of objective reality. However, measurements yield values characterizing a system, with the state of the system playing only a supporting role. The state is taken to be a maximum preparation of expectation values of observables. It is represented by a positive normalized linear functional on the algebra of observables. In a quantum context even the value attributed to an observable has only a weak ontological significance. It cannot generally be interpreted as revealing the value the observable possessed prior to the measurement. The values of quantities, or more generally observables considered as equivalence classes can be represented by an algebra.

I will give a simple presentation of some basic notions and refer to other sources for more details.[16] An algebra, $\mathcal{A}$ is a set of elements, $a, b, \ldots$ with one or more operations, O, such that a composition of two elements produces a new element that also belongs to the algebra: $a, b \,\epsilon\, \mathcal{A} \;\supset\; a\, O\, b \,\epsilon\, \mathcal{A}$. A C*-algebra is defined over a Banach space, a space with a norm. A Hilbert space is a Banach space with an inner product. On the presumption that basic algebraic notions are familiar, I will simply clarify two less familiar features, an involution and a norm. An involution (*) is a mapping with the properties:

$$\begin{aligned}(a + b)^* &= a^* + b^* \\ (ab)^* &= b^*\, a^* \\ (\alpha\, a)^* &= \overline{\alpha}\, a^* \\ (a^*)^* &= a, \quad \text{where } \alpha \text{ is a complex number.}\end{aligned}$$

The norm for an operator is defined in terms of the upper limit of its operation on a state function.

$$||A|| \;\equiv sup\, ||A\,\psi||/||\psi||$$

Both classical and quantum mechanics can be formulated in terms of a C*-algebra of observables. The distinguishing feature is that the classical algebra is abelian (or has commuting observables), while quantum algebra is non-abelian.

Quantum information theory involves qbits, rather than bits. A bit can take on a value of 0 or 1. A qbit involves a system that can take on one of two values in a measurement context. The usual description involves some semantic ambiguity. Consider an abstract specification of a two-valued quantum system,

$$\psi = \alpha\,|\,0> + \beta\,|\,1>, \text{ with } |\alpha|^2 + |\beta|^2 = 1$$

It is often claimed that a qbit can code an indefinitely large amount of information, since α and β take on continuous values. However, a qbit supplies information only in a measurement context. There it only has the values of 0 or 1. If 2 qbits are independent, then

$$\begin{aligned} |\psi> |\phi> &= (\alpha\,|\,0> + \beta\,|\,1>)(\gamma\,|0> + \delta\,|\,1>) \\ &= \alpha\gamma|0>|0> + \alpha\delta|0>|1> + \beta\gamma|1>|0> + \beta\delta|1>|1> \end{aligned}$$

This allows four possible values: $00, 01, 10, 11$. If $|\psi>$ and $|\phi>$ are entangled, then the system function is:

$$|\chi> = \epsilon|0>|0> + \zeta|0>|1> + \eta|1>|0> + \theta|1>|1>$$

The qbits do not have individual values until a measurement is performed.

With this background we return to the Why QM question. No individual experimental result necessitates the mathematics of quantum mechanics. Our variation on a theme by Bohr is that all experimental results must be expressed in physicalaes (or Extended Ordinary Language)as a necessary condition for unambiguous communication. The distinctive mathematics of quantum mechanics is generated by a consideration of paired observations, or of a preparation and an observation. The simple coupling of two observations is essentially extensional. It is compatible with any mathematical formulation that accommodates each separately. The complication comes from the assumption of inferential relations between the paired observations. Classical presuppositions do not supply the needed connection. Historically, this pairing was in terms of a complementary use of wave and particle representations. Now, however, we need to make the question much more specific. What feature of paired observations generates the distinctive mathematics characterizing QM?

Von Neumann's formulation showed how a limited from of the Why QM could be answered. His stated purpose was to develop a representation that unified the matrix and wave formulations without any reliance on the improper Dirac delta functions. Matrix mechanics used a discrete space, Z, that would have k indices for a particular problem. Wave mechanics would have a continuous space, Ω with k dimensions. These spaces are quite different. However, functions defined over them, F_Z and F_Ω, are isomorphic. Von Neumann developed this abstract function space as a Hilbert space. Then he showed that the commutation relations

$$[q_k, q_l] = 0, \quad [p_k, p_l] = 0, \quad [p_k, q_l] = \hbar\delta_{kl}$$

fixes the representation of p and q up to a unitary equivalence, a consequence of a theorem developed independently by von Neumann and Stone. This means that for a finite dimensional case the commutation relations determine the formalism. For von Neumann, the physical basis for the commutations relations stems from the way quantities are defined by measurements. His answer to the Why QM question covered only NRQM in a statistical interpretation.

Now there is a concerted effort to update von Neumann by using an information-theoretical formulation. Here the pairing comes from entangled systems. The foremost proposal to make

QIT a foundation for quantum mechanics is the paper by Clifton, Bub, and Halverson (henceforth CBH). It presupposes the entanglement consequences of the Bell theorem discussions and a C* -algebraic formulation of both classical and quantum theories. Instead of explaining the technical issues involved, I will give a very qualitative indication of how these relate to foundational problems. The von Neumann development showed that the indeterminacy relations entail the mathematical form of QM. Suppose that one could clone a quantum system, in something like the way we clone email. Then we could easily violate the indeterminacy principle by measuring complementary values on different copies. So perfect cloning is excluded. Any broadcast of information about a system's state can be supplemented by a later broadcast with different information. The Bell theorem discussions linked QM and relativity. Distant systems, or parts of one system, can be entangled. A measurement on one instantly reveals information about the other. If this could be made into a means of communication, then we would have a clear violation of special relativity. The transmission of secure information is the goal of quantum coding. If Eve, the evil eavesdropper, could copy Alice's message to Bob without leaving evidence of her interception, then information is not secure. So Alice and Bob rely on entangled systems for intercommunication, but must accept the restrictions this entails.

The BCH project raises three previously established claims to the status of QIT 'laws of nature':

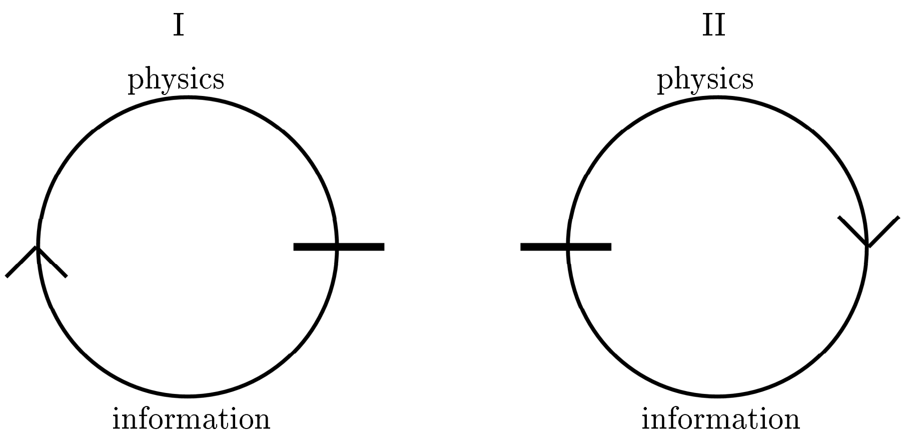
- the impossibility of superluminal information transfer between two physical systems by performing measurements on one of them;
- the impossibility of perfectly broadcasting the information contained in an unknown physical state; and
- the impossibility of unconditionally secure-bit commitment.

Within the general framework of a C* formulation of theories they show that these laws of nature entail:

- that the algebras of observables pertaining to distinct physical systems must commute—or kinematic independence;
- that any individual system's algebra of observables must be nonabelian, i.e., *non-commutative*;
- that the physical world must be *nonlocal*, in that spacelike separated systems must at least sometimes occupy entangled states.

If one accepts the contention that kinematic independence, non-commutativity, and non-locality are the general features characterizing quantum-mechanical systems, then the CBH paper is a derivation of QM from QIT. They also try to prove the converse, that the three physical characteristics entail the QIT postulates. This attempt, in their evaluation, is only partly successful because of an open question about bit commitment. This derivation grounds their contention that quantum theory should be interpreted as a theory about the possibility and impossibility of information transfer, rather than as a mechanical theory of waves and particles. Though epistemology is not developed, this clearly qualifies as an epistemological interpretation of quantum mechanics.

Alexei Grinbaum's impressive dissertation, "Le rôle de l'information dans la théorie quantique") develops a set of seven axioms used as a basis for deriving the Hilbert space formalism of QM. The axioms themselves should, he insists (p.37) be derived from a set of experimentally motivated postulates. Here quantum theory is explicitly presented as a theory about knowledge, not particles. He accommodates the epistemological circle by a distinction between: a P-observer, the observer as a physical system; and an I-observer, the observer as an intentional, or meta-theoretical agent. Enforcing the distinction involves cutting the epistemological circle at two different points.



If cut I is chosen, then physics is based on information. In cut II operations on information are based on physics. The specification of cuts is meta-theoretical. Of the seven axioms, three are explicitly quantum informational. The axioms stating the maximum information about any system may be altered by further information effectively replaces the CBH postulate on broadcasting.

There are technical difficulties with both proposals.[17] I will propose a different, non-technical, evaluation. Suppose that the basic objections can be met and that the CBH proposal, perhaps in a revised version, can be accepted as establishing the equivalence (or mutual deductibility) of QIT postulates and a specification of the features distinguishing QM from classical theories. What consequences would this have for the interpretation of quantum physics? Can it be established on an essentially epistemological foundation? The answer would be affirmative if one accepts the three CBH postulates as laws of nature. The general approach, however, is more like engineering than epistemology. One studies a system by introducing an input stimulus and then examining the resulting output. This stimulus-response system forms a channel. I find it misleading to treat such channels as primitives. Such channels are secondary support systems that presuppose primary support levels. One cannot treat foundational issues without an analysis of these more basic levels. A string of 1's and 0's may count as information in a computational context, but it is not yet information as knowledge.

I will indicate how such an analysis may be extended in two opposing directions. The first concerns epistemology. The term 'observable' stems from the empirical tradition of Hume, Mill, and Mach. In the present context, however, observables are interpretations of the results of positive operator valued measurements. It would be more accurate to label them 'communicables'. The difference has an interpretative significance. The CBH proposal is epistemological in the minimal negative sense that observables are taken as the basis for algebras, while states are stripped of ontological significance. However, epistemology as such is not treated. Grinbaum develops his epistemological position around an individual observer, considered both as a system and a meta-system. The meta-systematic issues concerning communicables require a consideration of the conditions of meaningful communication within a situated ongoing community of inquirers.

The opposing direction is a move from epistemology towards ontology. What does quantum mechanics tell us about reality? Here the QIT approach to foundations represents one step forward and one step backwards. The forward step is the acceptance of quantum mechanics as the basic science of physical reality. In principle, QM has long been accepted as basic. In practice, much of the effort spent on foundationalist interpretations, hidden variable interpretations, and Bell's theorem was geared towards reducing the strangeness of QM. The QIT approach accepts and exploits it. The step backwards is a methodological return to the epistemological limitations of the Copenhagen interpretation.

To compare the two we will rephrase Bohrian semantics in the terms of the epistemological circle. Classical physics is treated as an idealized system. Within a purely classical context the epistemological circle of classical physics is closed. Quantum physics, in a strict Bohrian interpretation, is an extension of classical physics. It relies on classical concepts to express all experimental information and treats theories as inference mechanisms. It is an epistemological interpretation in the sense that it relies on the epistemology of classical physics and on an explicit recognition of the limits of validity of classical physics. It does not extend classical ontology to the quantum realm and does not attempt to articulate an ontology proper to the quantum realm.

The QIT approach to foundations is based on a C*-formulation of theories. Both classical and quantum theories are formulated as theories of *observables*. The crucial difference is that the algebra proper to classical theories is abelian, while quantum theories are not abelian. Most of the work done in QIT is not concerned with ontological issues. However, when a QIT approach is coupled to a foundationalist perspective, then the ontological limitations are implicit in the methodology. A theory, whether formulated axiomatically or semantically, is seen as an inferentially closed system. The foundation determines the ontological significance of a theory. The CBH project is explicit on this point. An algebra of observables supplies a basis for formulating classical theories, NRQM, and QFT. Therefore, it supplies a basis for interpreting such theories. Though this differs significantly from the Bohrian formulation, it shares the same ontological limitations. The issue of an ontology proper to the quantum realm is bracketed.

In my view this minimal epistemological position should be treated as a point of departure, rather than as a foundation for interpretation. To answer interpretative questions about going beyond this limit we should consider the way the physics community went beyond such limits. The major advances beyond NRQM are RQM, nuclear physics, QED, and QFT. How should the ontological significance of these advances be clarified? Here the foundationalist approach is not very helpful. It has a developed method for interpreting properly formulated theories in terms of a correspondence between a mathematical formalism and the things the theory is about. None of the advances mentioned has ever received the type of formulation the foundationalist method presupposes.

An abstract version of axiomatic quantum field theory can be given a C^* - algebraic formulation. This version, however, only treats single particle systems, not interactions. It omits the standard model of basic particles. A reliance on this as a basis for ontological considerations effectively claims that an epistemological interpretation suffices because the methodology excludes ontology. This epistemological interpretation centers on an algebra of observables and the assumption that the net of algebras captures all the physically significant information. While 'observable' is generally separated from an observer by particle accelerators, bubble chambers, computer reconstructions of photographic tracks, and even budgetary problems, it still requires an operational anchor. The anchor is the spatio-temporal location of the observer and his/her measuring apparatus. This supplies the localization that makes observables local observables. An extension of this from NRQM to QFT requires a step-by-step advancement referenced by the observer's measuring apparatus. Julian Schwinger, and only Julian Schwinger, supplies this. In considering this and further advances we will be adopting an Ockhamist method of introducing ontology. His slogan, *Entia non sunt multiplicanda praeter necessitatem* also implies that when advances in physics make such an acceptance a matter of pragmatic necessity, then new ontology should be admitted.

3 Schwinger's Quantum Mechanics

In one of his final papers Schwinger characterized his method as "... a phenomenological theory—a coherent account that it anabatic (from anabasis: going up)"[18] Schwinger's development of NRQM used the distinctive features of quantum measurements to generate an algebra of measurements that yielded the basic mathematical formalism of QM. This can be related to the algebra of observables used in the QIT approach to the foundations of QM. Schwinger systematically extended this methodology to develop a measurement-centered formulation of QFT. Eventually, he rejected the quark hypothesis, local gauge field theory, and the standard model. I will use Schwinger's development both as a guide to a measurement centered approach to QFT, and also as a basis for appraising the limitations of this methodology. Since this material is not generally familiar and not easily accessible, I will provide more detail than in the other developments we are considering.

3.1 Schwinger's Measurement Interpretation.

Schwinger described his early student years as "unknown to him, a student of Dirac's" (Schweber, 1994, p. 278). Before beginning his freshman year at C.C.N.Y. he had studied Dirac's *Principles* and, at age 16, wrote his first paper, never published, "On the Interaction of Several Electrons", generalizing the Dirac-Fock-Podolsky many-time formulation of quantum electrodynamics. Schwinger repeatedly claimed that he was a self-taught physicist. That he could write such a paper before beginning college coupled to his notorious practice of skipping classes in college bears out this appraisal. The primary influence on his early education as a quantum physicist was Dirac' s *Principles.* He also seems to have been influenced by Bohr's accounts of the significance of measurement and the doctrine of complementarity. In the only philosophical talk he ever gave he called Bohr's complementarity principle "...perhaps the widest philosophical principle that has emerged from the study of microscopic systems" [19]. Schwinger followed Bohr and Dirac in taking physical concepts as basic and the mathematical formulation as a tool for expressing them: "I am not fundamentally a formalist—even though everyone thinks I am. The formalism is simply the language with which I express the physical ideas that have already been thought out" (Schweber, 365). He often expressed his position with the claim that mathematics should emerge from physics, not the other way around. (See Mehra and Milton, 2000, p. 356) Schwinger's systematic redevelopment of the Dirac formulation was presented in a series of lectures, some of which were privately circulated.[20]

Schwinger begins his measurement account with the claim: "Quantum mechanics is a symbolic expression of laws of microscopic measurement" (Schwinger 1970a, 1) If this is so, then one should begin with the distinctive features capturing these measurements, the answer to the Why QM question. This, for Schwinger, is the fact that successive measurements can yield incompatible results. Since state preparations also capture this feature Schwinger actually uses state preparations, rather than complete measurements as his starting point. I will summarize the basic development (Schwinger, 1970a) and then consider some objections.

He begins by symbolizing a measurement, M, of a quantity, A, as an operation that sorts an ensemble into sub-ensembles characterized by their A values, $M(a_i)$ The paradigm case is a Stern-Gerlach filter sorting a beam of atoms into two or more beams.[21] This is, in Pauli's terms, a type one measurement. An immediate repetition would yield the same results. There is no reduction of the wave packet or recording of numerical results. An idealization of successive measurements is used to characterize the distinguishing feature of these microscopic measurements. Symbolically

$$M(a')M(a'') = \delta(a', a'')M(a'). \tag{9}$$

This can be expanded into a complete measurement, $M(a') = \prod_{i=1}^{k} M(a'_i)$ where a_i stands for a complete set of compatible physical quantities. Using A, B, C and D for complete sets of compatible quantities, a more general compound measurement is one in which systems are accepted only in the state $B = b_i$ and emerge in the state, $A = a_i$, e.g., an S-G filter that only accepts atoms with $\sigma_z = +1$ and only emits atoms with $\sigma_x = +1$. Measurement symbols are read from right to left. This is symbolized $M(a_i, b_i)$. If this is followed by another compound measurement $M(c_i, d_i)$, the net result is equivalent to an overall measurement that only accepts systems in state d_i and emits systems in state a_i. Symbolically,

$$M(a_i, b_i)M(c_i, d_i) =< b_i|c_i > M(a_i, d_i). \tag{10}$$

For this to be interpreted as a measurement $< b_i|c_i >$ must be a number characterizing systems with $C = c_i$ that are accepted as having $B = b_i$. The totality of such numbers, $< a'|b' >$, is called the transformation function, relating a description of a system in terms of the complete set of compatible physical quantities, B, to a description in terms of the complete compatible set, A. A little manipulation reveals that N, the total number of states in a complete measurement, is independent of the particular choice of complete physical quantities. For N states the measurement symbols form an algebra of dimensionality N^2. These measurement operators form a set that is linear, associative, and non-commutative under multiplication.

To get a physical interpretation of this algebra consider the sequence of selective measurements $M(b')M(a')M(b')$. This differs from a simple or repeated measurement $M(b')$ in virtue of the disturbance produced by the intermediate $M(a')$ measurement. This suggests $M(b')M(a')M(b') = p(a', b')M(b')$, where $p(a', b') =< a'|b' >< b'|a' >$. Since this is invariant under the transformation, $< a'|b' >\rightarrow \lambda(a') < a'|b' > \lambda(b^{-1})$, where $\lambda(a'), \lambda(b')$ are arbitrary numbers, Schwinger argues that only the product, $p(a', b')$ should be accorded physical significance. Using $\sum_{a'} p(a', b') = 1$ Schwinger interprets this as a probability and imposes the restriction,

$$< b'|a' >=< a'|b' >^* . \tag{11}$$

The use of complex numbers in the measurement algebra implies the existence of a dual algebra in which all numbers are replaced by complex conjugate numbers. This algebra of measurement operators can be expanded into a geometry of states. Introduce the fictional null (or vacuum) state, 0, and then expand $M(a', b')$ as a product, $M(a', 0)M(0, b')$. Let $M(0, b') = \mathbf{\Phi}(b')$, the annihilation of a system in state b', and $M(a', 0) = \mathbf{\Psi}(a')$, the creation of a system in state a'. These play the role of the state vectors, $\mathbf{\Phi}(b') =< b'|$ and $\mathbf{\Psi}(a') = |a' >$. With the convenient fiction that every hermitian operator symbolizes a property and every unit vector a state one can calculate standard expectation values.

Schwinger follows Dirac's precedent of not assuming Hilbert space, but simply constructing a functional space on the basis of physical arguments. This practice can generate the same type of criticisms concerning rigor that the Dirac formulation encountered. Thus, (11) introduces the complex numbers needed for a complex vector space. Dirac had introduced a complex vector space on physical grounds. The direction of a vector represents the state of a system. The state of a photon includes polarization, best represented by a phase in a complex space. In Schwinger's reformulation, measurements and transformations are basic, rather than states and vectors. In this context (11) seems to lack physical justification, since measurements only yield real numbers. Gottfried (201) justifies the use of a complex space by appealing to the wisdom of hindsight.

This difficulty supplied the point of departure for a series of papers in which Accardi sought to put this algebra on a more secure basis. (See Accardi 1995) Accardi's work supplies a bridge for comparing Schwinger's algebra of observables with the C*-algebra just considered. Accardi followed Schwinger's precedent of treating measurements as filters sorting an ensemble into sub-ensembles. He defined an algebra of measurements as a quintuple,

$$\{\mathcal{M}, \bullet, +, *, \text{multiplication by}\, p \,\epsilon\, [0, 1]\},$$

where $\mathcal{M}$ is a set whose elements, X, Y, Z, represent measurements (or preparations, or apparatuses); $\bullet$ represents consecutive performances; $*$ time reversal; $+$ simultaneous measurements; and these operations satisfy probability axioms. Further, $A \,\epsilon\, \mathcal{M}$ is a projection if $A = A^*$ and $A^2 = A$. Then there is an injective map of $\mathcal{M}$ into a *-algebra, $\mathcal{A}$.

Classical measurements, by definition, are those for which all measurements commute. This implies a unique maximal partition of the identity.

A formal approach to quantum measurement is based on an information-theoretic version of the Heisenberg principle: *There exists pairs of observables which cannot be simultaneously measured with arbitrary precision on the same system.* The weak form of this theorem is that there exists two maximal partitions of the identity, (A_α), (B_β), where a maximal partition corresponds to a complete set of compatible observables. Then a Schwinger algebra of rank n is defined as an ordered triplet, $\{\mathcal{A}\,, T\,, (A(x))_{x\,\epsilon\,T}\}$, where $\mathcal{A}$ is a real, associative *-algebra, T is a set, and for every x in T, $A(x) = \{A_1(x), \cdots, A_n(x)\}$ is a maximum partition of the identity in $\mathcal{A}$, whose self-adjoint members $(A_j = A_j^*)$ are observables. Accardi proves that two maximal observables in a Schwinger algebra define a transition probability matrix with the symmetry properties of the standard Hilbert-space model of quantum mechanics. He also establishes the converse. Roughly, given a family of observable quantities and a transition probability matrix for pairs of values, then the Heisenberg principle generates a Schwinger algebra. Finally, he shows that a family of transition probabilities admits of a Hilbert-space model. This not only puts Schwinger's development of a more rigorous basis; it also relates it to standard formulations of quantum mechanics. Thus, Schwinger's methodology is compatible with a standard Hilbert- space formulation of quantum mechanics, even though it may not strictly generate it.

This is most easily compared with Grinbaum's attempt to use quantum information theory as a foundation for quantum mechanics. He has 7 axioms, but insists that these should have a physical basis in measurement. The assumption is that the results of all measurements can be digitized and embedded in a C*-algebra. This, in turn, supports a structure isomorphic to the structure of subspaces of a Hilbert space. In principle, one could have a real, a complex, or a quaternion Hilbert space. Neither the measurement process nor the C*-algebra supplies a basis for choosing between these forms. The practice of physics selects a complex Hilbert space as the most convenient form. From our perspective, the crucial difference between Schwinger's and the QIT method is that Schwinger's method can be systematically extended to QFT. First we consider a preliminary point that applies to NRQM and QFT.

While quantum kinematics can be developed from first principles, quantum dynamics was never so straightforward. Traditionally, one sets up a classical Hamiltonian for some problem, uses operator substitutions to get a quantum Hamiltonian, and then compares the solution of this idealized problem with physical situations. Schwinger saw his work on QED as paving the way for a more systematic development of quantum dynamics, one that could be extended to QFT. "The evolutionary process by which relativistic field theory was escaping from the confines of its non-relativistic heritage culminate in a complete reconstruction of the foundation of quantum dynamics" (Schwinger 1958, xiv).

The new dynamics is based on a unitary action principle whose justification hinges on the foundational role assigned measurement. A measurement-apparatus effectively defines a spatio-temporal coordinate system with respect to which physical properties are specified. A transformation function, $< a't_1|a''t_2 >$, relates two arbitrary complete descriptions. Physical properties and their spectra of values should not depend on which of equivalent descriptions are chosen. Hence, there must be a continuous unitary transformation leading from any given descriptive basis to equivalent bases. The continuous specification of a system in time gives the dynamics of the system (See Gottfried,1966, pp. 233- 256). From this Schwinger infers that the properties of specific systems must be completely contained in a dynamical principle that characterizes the general transformation function.

Any infinitesimal alteration of the transformation function can be expressed as

$$\delta < a_1' t_1 | a_2'' t_2 >= i < a_1' t_1 | \delta \mathbf{W_{12}} | a_2'' t_2 > . \tag{12}$$

This suggests the fundamental dynamical postulate: There exists a special class of infinitesimal alterations for which the associated operators $\delta\mathbf{W_{12}}$ are obtained by appropriate variation of a single operator, the action operator $\mathbf{W_{12}}$, or $\delta\mathbf{W_{12}} = \delta[\mathbf{W_{12}}]$. Thus, quantum dynamics can be developed simply as an extension of the algebra of measurements without attaching any further ontological significance to state functions. This is the measurement interpretation in its starkest form. Once the action principle is established Lagrangians follow in a familiar fashion. In Schwinger's account QFT follows as an extension of the measurement-based development of quantum mechanics.

3.2 Adiabatic Quantum Field Theory

Methodologically we can distinguish three approaches to QFT: Lagrangian, algebraic, and anabatic. By 'Lagrangian' we refer to the common method of specifying fields through Lagrangians, which are obtained by a variational principle or any other convenient means. This is the physics that led to electroweak unification and the standard model. In spite of these outstanding successes, some would argue that it is methodologically deficient in two different respects. Mathematically, Lagrangian QFT (LQFT) has never been given a rigorous formulation and involves renormalization procedures and series expansions that require, but lack, adequate mathematical justification. Methodologically, LQFT often relies on postulation, rather than step-by-step advancement from an established basis. Algebraic QFT (AQFT, aka axiomatic QFT and local QFT) is an attempt to give QFT a rigorous mathematical formulation. AQFT is seriously deficient from a physical perspective. It treats only free fields, but not interactions. This, in turn, involves omitting the standard model and its particle ontology. With this ontology omitted an epistemological interpretation suffices. Anabatic QFT (SQFT, aka Schwinger's QFT) involves the rigorous following of a step-by-step methodology of advance from a minimal epistemological basis. Mathematical or methodological purity is achieved at a high price. Neither AQFT nor SQFT includes the standard model and its particle ontology.

LQFT and AQFT receive detailed coverage in many textbooks and graduate courses. Though many of Schwinger's contributions remain as permanent parts of QFT, his anabatic methodology hardly casts a shadow across the broad plains of contemporary particle physics. Nevertheless, it is precisely what we need to clarify the extension of the epistemological/ontological circle previously considered. The epistemological interpretation centers on an algebra of observables and the assumption that the net of algebras captures all the physically significant information. Extensions are anchored in the spatio-temporal location of the observer and his/her measuring apparatus. This supplies the localization that makes observables local observables. The anabatic method supplies a step-by-step advancement referenced by the observer's measuring apparatus. Schwinger, and only Schwinger, supplies this. We will exploit his work in two ways. First, his meticulous following of a strict methodology involved a careful distinction between advances achieved by the methodology of a master craftsman and explicit postulation. In 1960 Schwinger was clearly the leading quantum field theorist. When QFT was revived in the early 1970's Schwinger was out of the loop and abandoned field theory in favor of his new source theory. The advances LQFT made beyond Schwinger's limits rely on a postulational basis. This has an ontological significance that invites critical analysis.

The distinctive aspects of Schwinger's methodology are easily lost in the technical details. It may help to highlight some basic points before beginning the survey. First, the space-time framework is that proper to an observer and her measuring apparatus. As we will see, this grounds systematic extensions. Second, he builds on his development of the measurement interpretation. Third, His anabatic methodology plays a basic role. Fourth, Schwinger always insisted on a careful distinction between a phenomenological and a depth level. The term 'phenomenological' occurs in almost every abstract of Schwinger's later papers. He considered operator field theory as fundamental and all higher levels as phenomenological. The coupling of his strict usage of the term with his methodology led to conflicts on two issues. The first concerned particles. "I contend that the fundamental dynamical variables are field operators while particles are identified as the stable or quasistable excitations of the coupled field system."(Schwinger, 1964a, Note 3). Schwinger's field operators have a quasi-ontological status. The Bohr-Rosenfeld (1933, 1950) analysis showed that measured field values correspond to smeared out averages over volumes proper to classical test particles. Such smeared out values should be represented by operator-valued distributions. Schwinger assumed field values at spatio-temporal points, not smeared out values. However, he did not accord quantum fields an ontological status. The classical concept of particles as small localized objects still flourished in experimental physics. The basic data stemmed from particle collisions. Schwinger coordinated the two levels by identifying the phenomenological concept 'particle' with small regions of space possessing high energy density. This interpretation of particles did not accord hypotheses concerning particles a fundamental role in quantum field theory. The second issue was the type of questions phenomenological accounts could answer. They could supply descriptive accounts, classifications of properties and interactions, and mathematical formulas. They could not supply the requisite depth account or its key theoretical ingredients.

Schwinger's collection of basic papers on QED contained the evaluation: "The post-war development of quantum electrodynamics have been largely dominated by questions of formalism and technique, and do not contain any fundamental improvement in the physical foundations of the theory."(Schwinger 1958, p. xv). What constrained the needed fundamental improvements were the limitations of the measurement interpretation. QED assumed that electron and photon fields could be treated as independent fields and then interactions were added. Measurement of these fields, however, essentially depended on interactions; "It seems that we have reached the limits of the quantum theory of measurement, which asserts the possibility of instantaneous observations, without reference to specific agencies ... We conclude that a convergent theory cannot be formulated within the framework of present space-time concepts." (Schwinger, 1958, p. xvi)

When Schwinger turned from QED to QFT he did not have the desired new convergent theory. However, he did have two methodological advances. The first was in quantum dynamics where his action principle replaces a dependence on the correspondence principle. The second, operator fields, will be considered shortly. In spite of Schwinger's dominance, the standard QFT of the early 1960's differed from Schwinger's.[22] Schwinger's methodology led to long complicated deductions from variations of an action principle. Oppenheimer's famous appraisal indicates the difficulty people had in following Schwinger's long intricate calculations: "Others calculate to show how it is done; Julie calculates to show that only he can do it." It was easier to rely on the fiction of second quantization, treating the Klein-Gordon and Dirac equations as if they were classical field equations. The field equations can be formulated in terms of creation and annihilation operators creating and annihilating the appropriate particles. For Schwinger, as noted, 'particle' is a phenomenological concept. The carriers of physical properties are volume elements of three-dimensional space.

In accord with the correspondence principle, the most basic physical properties are energy and momentum. To accord with relativity, disjoint or spacelike volumes are physically independent and contribute additively to total energy and momentum. In terms of an energy-momentum tensor, $P^0 = \int \mathbf{dx}\, T^{00}(\mathbf{x})$; $P^k = \int \mathbf{dx}\; T^{0k}(\mathbf{x})$. T^{00} and T^{0k} are functions of a dynamic variable, $\mathbf{x}$, at time t. These dynamic variables, or operator fields, supply the theoretical concepts that replace the phenomenological concept 'particle'. This is the basic conceptual advance that Schwinger makes beyond Bohr's methodology. For Bohr all descriptions must be expressed exclusively in classical terms. Schwinger assumes that it is possible to use dynamical field variables to give a sub-microscopic descriptive account within the framework of his methodology. The spatial and temporal coordinates that serve as parameters for operator fields are idealized extensions of the spatio-temporal framework of the measuring apparatus. It is the action principle, in differential format, that allows for a systematic extension of this framework to sub-microscopic field descriptions: "It is the introduction of operator variations that cuts the umbilical cord of the correspondence principle and brings quantum mechanics to full maturity" (Schwinger, 1983, p. 343).

The immediate problem is to introduce these dynamic variables in a systematic way that accords with relativity and a measurement-based quantum mechanics, and then develop them in a way that explains the phenomenology of particles. A measured value corresponds to a scalar product, $< a|b >$. If this measurement does not depend on location, or time, or any continuous parameter change, then there must be a corresponding unitary transformation, $|b' >= U|b >, < a'| =< a|U^{-1}$ so that $< a|b >=< a'|b' >$. As before, an infinitesimal alteration of the transformation function can be expressed as $\delta < a|b >= i < a|\delta W|b >$. For the transformation function, $U = 1 - iG$, G, the Green's function, is the generator of the transformation. Schwinger interpreted the Green's function as the propagation of an infinitesimal disturbance and insisted that all physically significant information about a system could be explained in terms of Green's functions. In non-relativistic quantum mechanics the action has the form, $W_{12} = \int_{t_2}^{t_1} L(t)dt$

The Lagrangian can be written in different canonical forms that differ only by a total time derivative. Writing a Lagrangian symmetrical in p and q variables and using $\chi_a(a =$

$1, 2, \ldots, 2n$) to cover the canonical $p's$ and $q's$ the Lagrangian can be written

$$L = \sum_{a=1}^{2n} 1/2(\chi_a A_{ab}\, d\chi_b/dt) - H(\chi, t). \tag{13}$$

For L to be scalar, A must be a skew-Hermitian matrix (or $A^{*T}_{ab} = -A_{ba}$, where * and ^{T} indicate complex conjugate and transpose). It can be written as the sum of an anti-symmetrical real matrix, a, and a symmetrical imaginary matrix, s. This leads to two kinematically independent types of variables, one obeying commutation relations and one anti-commutation relations. Here field theory and relativity impose separate but related constraints. A quantum state is specified by particular values of an optimum set of compatible physical quantities. Schwinger assumes determinism in the sense that the state of a system at one time determines its state at a later time. Relativity requires that there be no causal relation between regions with a space-like separation, implying that measurements individually associated with different regions in space-like relation are causally independent. This leads to an indefinitely large number of degrees of freedom associated with each separate region. Here again, Schwinger explicitly anchors such considerations in the measurement methodology. "An infinite total spatial volume is an idealization of the finite volume defined by the macroscopic measurement apparatus"[23] Each such region is characterized by its own Lagrangian density $\mathcal{L}$, with $L = \int \mathcal{L}(\mathbf{dx})$. Analogy with L suggests

$$\mathcal{L} = \frac{1}{2}\sum_{a=1}^{n} \chi_a\, A^{\mu}_{ab}\partial_\mu\, \chi_b - \mathcal{H}(\chi). \tag{14}$$

To be relativistic Eq. (14) does not single out a time variable. "Time appears in quantum mechanics as a continuous parameter which represents an abstraction of the dynamical role of the measurement apparatus" (Schwinger, 1972, 142). The requirement that measurements performed at the same time in distinct regions do not interfere can be generalized to a space-like surface, σ, leading to $W_{12} = \int_{\sigma_2}^{\sigma_1}(d_4\chi)\mathcal{L}$

The extension of the action principle presents a technical problem. One can use canonical transformations to go to arbitrary coordinate frameworks. However, the description of spin requires the introduction at each point of an independent Lorentz frame, combined with the demand of invariance under local Lorentz transformations. To get locality one must begin with a value at a point and then determine under what conditions its value depends only on immediately adjacent points. This requires an infinitesimal transformation which can be written $\delta x_\nu = \delta\epsilon_\nu + \delta\omega_{\mu\nu}x^\mu$. For a conservative non-relativistic system the generator for a time transformation is $G_t = -Hdt$. By analogy the general coordinate displacement for a relativistic system is $G_x = \int_\sigma d\sigma_\mu T^{\mu\nu}\delta_\nu$, leading to $G_x = \delta\epsilon_\nu + 1/2\,\delta\omega_{\mu\nu}J^{\mu\nu}$, where we use natural units ($\hbar = 1; c = 1$), and the Einstein summation convention. The familiar momentum and angular momentum symbols function as generators defined as integrals of the stress-energy tensor:

$$P^\nu = \int_\sigma d\sigma_\mu T^{\mu\nu},\ J^{\mu\nu} = \int_\sigma [x^\mu T^{\lambda\nu} - x^\nu T^{\lambda\mu}] \tag{15}$$

This gives the basic consistency conditions for any relativistic quantum field theory. The general prescription is the same for all fields. Introduce field variables from which one can construct the energy-momentum density. Use this to construct the P and J terms. The fact that successive measurements interfere is expressed mathematically by commutation relations. So one must work out the commutation relations for the P and J terms. To define a local system consider a local observer on a space-like surface, σ, with the unit normal, η, giving the local time. The local energy-density is $T^{(0)(0)} = \eta_\mu T^{\mu\nu}\eta_\nu$. One may define a local system as one for which the local energy density is a function only of the fundamental dynamical variables at the location for which this is defined. This leads to the basic equal-time commutation relation,

$$1/i\ [T^{0\,0}(x), T^{0\,0}(x')] = -\partial_k \delta(x - x')[T^{0k}(x) + T^{0k}(x')] \tag{16}$$

This is sufficient to ensure the Lorentz invariance of the theory. Schwinger considered Eq. (16) the most fundamental equation of relativistic quantum field theory (Schwinger, 1962, p. 409). It is not an axiom of a new theory and does involve any assumptions concerning the ontology of fields. It is based on extending the space-time framework set by the measurement apparatus to sub- microscopic volumes characterized by field variables in a way that accords with relativistic invariance. On this basis one can construct particular types of fields without assuming either that there is a classical field expressed in c- numbers which gets second quantized to q-numbers, of that 'particle' functions as anything more than a phenomenological term.

I will indicate how this program is implemented for the three basic fields. For a scalar field make the simplest assumption of a one-component Hermitian field, $\phi(x)$ Since in Eq. (14) the gradient appears linearly the way to keep the Lagrangian a Lorentz-invariant scalar is to introduce a supplementary 4-vector field, $\phi^\mu(x)$. This leads to the Lagrangian density,

$$\mathcal{L} = -\phi^\mu \partial_\mu \phi + 1/2\, \phi^\mu \phi_\mu - \mathcal{H}(\phi) \tag{17}$$

For a massive particle $\mathcal{H}(\phi)$ is a scalar only if it has the form $\mathcal{H}(\phi) = (1/2)m\phi^2$. From these field variables one can construct a $T^{0\,0}$ and $T^{0\,k}$ that satisfy the fundamental commutator relations for local fields.

For vector fields denote by ϕ_μ the Hermitian vector field that transforms as a 4-vector. Since the gradient of this appears linearly in the Lagrangian one can preserve its Lorentz invariance by introducing a second-rank anti-symmetrical tensor, $G_{\mu\nu}$. Then the Lagrangian density corresponding to non-interacting fields is

$$\mathcal{L} = 1/2\, G^{\mu\nu}(\partial_\mu \phi_\nu - \partial_\nu \phi_\mu) + 1/4\, G^{\mu\nu} G_{\mu\nu} - (m^2/2)\phi^\mu \phi_\mu \tag{18}$$

With this Lagrangian Schwinger can generate the equations of motion and constraint. Instead of constructing the energy-momentum density from these variables Schwinger reverses his procedure by imposing commutation relations and then, by considerable manipulation, constructing the energy-momentum density. This leads to a local field theory. The identification of $G^{\mu\nu}$ with the familiar $F^{\mu\nu}$ used in the relativistic formulation of Maxwell's equations yields the Lagrangian that most derive by beginning with classical electrodynamics (Schwinger, 1965, pp. 175-80).

For spin 1/2 fields recollect eq. (13) and the observation that A^μ must be skew-hermitian. This can be accomplished either by having A^μ real and antisymmetric or imaginary and symmetric. A heuristic argument leads to commutation relations for the real A^μ and anti-commutation relations for imaginary A^μ. Rewriting A^μ as $i\alpha^\mu$, where α^μ is a Dirac matrix, leads to the familiar Lagrangian,

$$\mathcal{L} = i/4\,[\psi\alpha^\mu\partial_\mu\psi \,-\, \partial_\mu\psi\alpha^\mu\psi] \,-\, \mathcal{H}. \tag{19}$$

With the assumption that each component of the field ψ is a dynamic variable with its own equation of motion Schwinger constructs an energy density, gets the commutator, shows that the results fits the consistency conditions Eq. (16) and yield the Dirac equation.

Schwinger does not strictly derive these Lagrangians from first principles. There are various plausibility considerations and heuristic arguments. In the light of previous discussions it is important to note the stress on a single framework. His methodology begins with a measurement-based interpretation of quantum mechanics and extends this to relativistic field theory by assuming that field variables can be used to give a descriptive account within the framework of field theory on a submicroscopic level. The spatio-temporal coordinates used as parameters for these field variables are idealized extensions of the measuring-apparatus framework. Within this framework one can associate the phenomenological concept 'particle' with a limited space- time region characterized by definite values for basic parameters.

The crucial problem in the mid-1960's was extending quantum mechanics to treat weak and strong interactions. The widely shared view that QFT did not work motivated alternative approaches, attempts to supplement or replace QFT by any method that allowed calculations and experimental checks. Most of these methods, such as S-matrix theory or a reliance on dispersion relations, would be classified as phenomenological. The principal difference in Schwinger's phenomenology came from his following of a step-by-step methodology of advancement. In the mid 1960's his basic method was to supplement the field theory just considered by hypotheses concerning weak and strong interactions.

For weak interactions Schwinger (1957) proposed the existence of an isotropic triplet of vector bosons to include both weak and electromagnetic interactions, with massive Z-particles mediating the weak interactions[24]. This was the beginning of the vector- boson theory of electroweak interactions. Subsequent advances came from the discovery of parity non-conservation in weak interactions, the proposal that weak interactions were vector—axial-vector couplings, and the partially conserved current hypothesis (Cao, 1998, pp. 229-240). Schwinger assigned his student, Glashow, electroweak interactions as a dissertation topic (Glashow, 1996). In (Schwinger, 1962b) he tackled a fundamental difficulty of electroweak theory. Gauge invariance for a vector field coupled to a dynamic current implies the existence of massless bosons, rather than the massive bosons Schwinger's account postulated. He suggested that vacuum fluctuations of the A_μ field could be split into two parts, one of which would confer mass on bosons. This suggestion eventually blossomed into the Higgs mechanism that was incorporated in the Weinberg-Salam electroweak theory (Higgs, 1997).

Schwinger developed a methodology for weak interactions that coupled the phenomenological and depth levels. He assumed that each lepton is correlated with a field variable. Corresponding to the particles, $\nu, \mu^+, e^-, \bar{\nu}, \bar{\mu}$, and e^+, were the fields, $\chi_1, \chi_2, \chi_3, \bar{\chi_1}, \bar{\chi_2}, \bar{\chi_3}$. Similarly for lepton pairs there are corresponding fields of a vector–axial-vector form. Thus for the pair consisting of a muon and a right helicity neutrino there is a field current, $\chi_1\gamma^\mu(1+i\gamma_5)\chi_2$. These currents are then coupled to the hypothetical Z-field. Finally, the Lagrangian adds together all the interaction terms. The electroweak theory developed by Weinberg and Salam differed from Schwinger's, but was compatible with his principles. When Schwinger moved to California in 1971 he took a new vanity license plate, $A137Z$.

He never reached a similar accord on strong interactions. In 1965 there was a considerable amount of experimental information concerning strongly interacting particles and a phenomenological systematization (Gell-Mann, 1964, pp. 11-57) in Gell-Mann's widely circulated summary of the eightfold way. Schwinger announced, "A complete dynamical theory of matter is now to be constructed on the basis of various analogies, arguments and hopes" (Schwinger, 1965b, p. 213). The basic analogy is between weak and strong interactions. Schwinger's form or electroweak unification involved two fields: a zero-mass electromagnetic field coupled to an electronic charge Q; and a massive Z-field, coupled to changes in charge, ΔQ. Analogy suggests two strong fields: a zero mass B-field coupled to the nucleonic charge N; and a massive V-field coupled to the change in nucleonic charge, ΔN. The most plausible assumption is that the multicomponent vector field, V has three charged components, yielding a three- fold way. The analogy breaks down in the field-particle correlation. For strong interactions it is not possible to correlate one field with each particle. Nucleons and mesons seem to be composites and should be associated with composite fields.

In 1964 Gell-Mann and Zweig independently introduced the quark hypothesis, which Schwinger rejected. Schwinger's rejection had strong roots in his ideas of the proper relation between a phenomenological and depth level. 'Particle' functions on the phenomenological level. Speaking of a particle assumption he claimed: "But the essential point is embodied in the view that the observed physical world is the outcome of the dynamic play among underlying primary fields, and the relationship between these fundamental fields and the phenomenological particles can be comparatively remote, in contrast to the immediate connection that is commonly assumed" (Schwinger 1965, p. 189). The quark hypothesis entered on the wrong level, as part of an underlying theory rather than the phenomenology, and entered through a phenomenological classification, rather than a depth theory.

The quark hypothesis soon led to quantum chromodynamics and the standard model. These Schwinger rejected. This rejection was undoubtedly due to a complex of personal and professional factors. Here again, however, the rejection was consonant with Schwinger's methodology. The phenomenological level, based on particles, related to the depth level, based on operator fields, through a complex process of adjustment. The fundamental difficulty was that there was no underlying theory. There was a framework for a theory together with constraints and anticipations. The crucial anticipation concerned coupling constants. It was necessary to assume coupling constants that fit the phenomenological data. "The explanation of these coupling constants is a goal of the fundamental theory."(Schwinger, 1965b, p. 270) The standard model does not supply these coupling constants. They are inserted by hand based on fitting the observed data. This clearly does not meet the requirements Schwinger set for himself and for field theory.

In one of his final field theory papers Schwinger claimed: "In view of the serious technical obstacles to performing field theory calculations from first principles, it is useful to convert the characteristic ideas of this field theory of matter into a corresponding phenomenology."

(Schwinger, 1964b, p. B1823) Schwinger compared his new methodology to the treatment of molecules in NRQM. There one has experimental data and an underlying theory, the Schrödinger equation. Yet, it is never, or hardly ever, possible to deduce the data from the Schrödinger equation. So, there are phenomenological models that reflect the underlying theory and are adjusted to fit the data.

This switch to phenomenological fields led to source theory, the central theme of Schwinger's subsequent work.[25] He presented this as a mean between two extremes: operator field theory, which takes fields as basic and particles as phenomenological manifestations; and S-matrix theory, which takes particles as basic. Both receive the same criticism: "Is it not possible to separate particle phenomenology from speculations about particle structure?"(Schwinger, 1970b, pp. 34, 36). I will simply indicate the basic principles, which are clear even without the details. The source of a particle is a collision in a finite space- time region where other particles combine to produce a new particle (or modify an old one). Resonances are not admitted to the status of particles unless they exhibit the same characteristics in different reactions. In source theory one abstracts the conferral of properties and represents it through a source function, $S(x)$. The effectiveness of the source in supplying energy and momentum is described by another function, $S(p)$, and $S(p) = \int (dx) e^{-ipx} S(x)$ expresses the complementarity relation between them. A sink destroys the particle and transfers it properties to other particles. The probability amplitudes for creating (and annihilating) a particle with a momentum $\mathbf{p}$ is symbolized $< 1_p|0_- >^2$ ($< 0_+|1_p >^2$). The two are combined in the probability amplitude $< 0_+|0_- >^2$. The testing ground for this was QED, where Schwinger reproduced the older results without divergences or renormalization.

A half century ago *Time* magazine (8 Nov. 1957, p. 24) described Schwinger as 'heir apparent to the mantle of Einstein'. The mantle eventually covered a resemblance not anticipated in 1957. Both physicists in their later years rejected an overwhelmingly successful version of quantum mechanics because it did not embody their ideals of what the true theory should be. There is widespread agreement that the standard model is not the ultimate theory and that the ultimate theory should yield basic coupling constants. But, there is a virtually unanimous consensus that the standard model supplies a better basis for treating fundamental particles and interactions than Schwinger's Source theory or his dyon model, which we have not treated. Gell-Mann has repeatedly argued that the measurement interpretation, or the approximate quantum mechanics of measured systems, needs replacement because quantum cosmology and decoherence are beyond the limits of validity of any measurement interpretation. (Gell-Mann, 1994a, p. 135). I believe that the standard model not only goes beyond what the founders of the measurement interpretation intended, but also any plausible anabatic extension of that basis. To add flesh to this bare claim, we should first comment on the methodological problems involved.

4 The Standard Model

The standard model is the outcome of the Lagrangian field theory approach and of unprecedently close cooperation between theoreticians and experimenters. It is a difficult topic, but one well covered in many texts.[26] When judged by the standards set by either SQFT or AQFT, the standard model has some serious shortcomings. Schwinger insisted that the ultimate theory should explain the coupling constants. The standard model does not do this. It is now widely regarded, not as the ultimate theory, but as a relatively low-energy approximation to a deeper theory at a much higher energy level. Also, where Schwinger relied on a step-by- step advance and restricted postulation to the minimum necessary for advance, both components of the standard model rely on postulation.

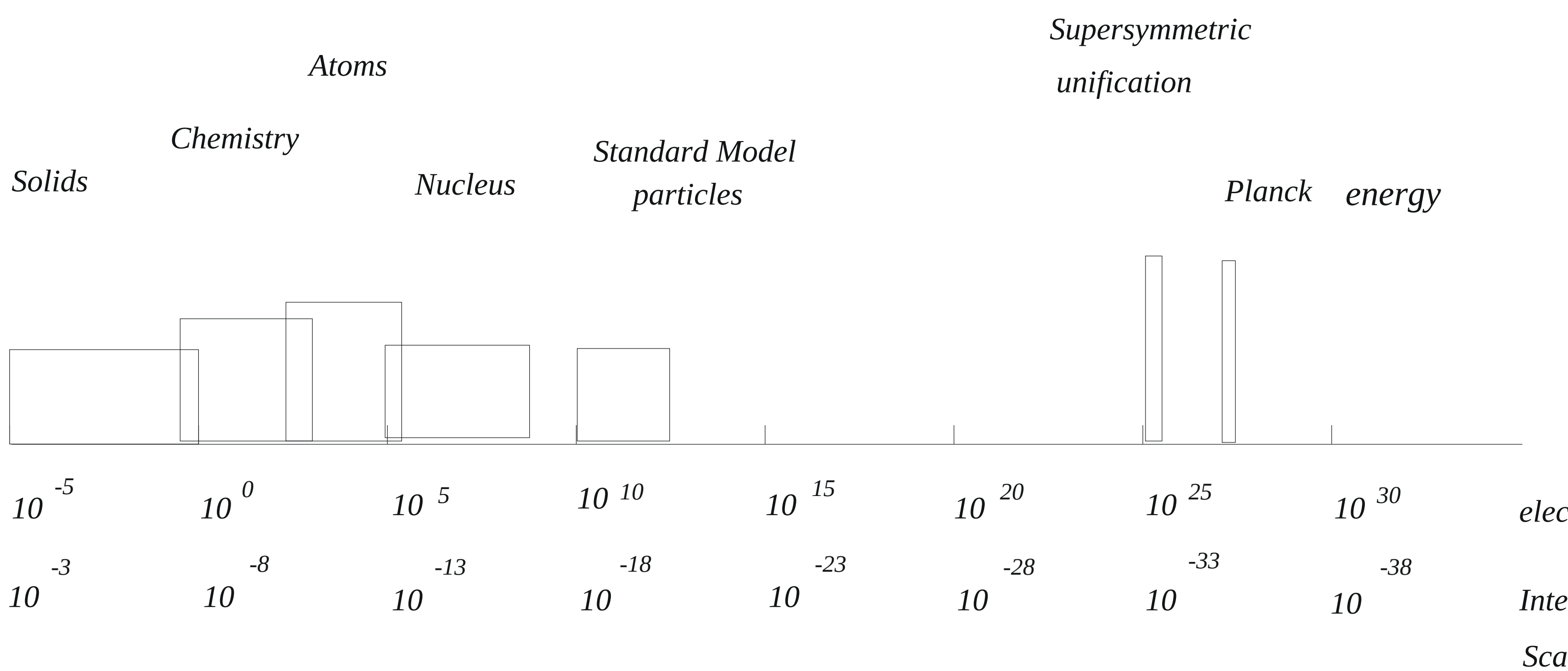
Algebraic QFT prizes the virtues of mathematical rigor and consistency.[27] It is also relatively clear on the epistemology/ontology circle. Instead of beginning with specific models one begins with the general principles of quantum mechanics and relativity. In this context 'field' does not have any basic ontological significance. Measured fields correspond to smeared out averages over a spatio-temporal volume. The mathematical representation of fields should be regarded as operator valued distributions, rather than physical values at a point. The basic things treated are observables, rather than fields. In this context 'observable' is only distantly related to a process of observing or measuring. 'Observable' effectively means represented by bounded operators in a Hilbert space. For each compact space-time region one constructs a local algebra (a von Neumann algebra) of observables. Relativity and QM enter with the assumption that operators in causally separate regions commute. Then the physical significance of the theory is contained in the net of maps from space- time regions to algebras. This minimalist ontology is consistent with the epistemological basis in experimental knowledge, at least in the abstract. This formulation supplies a basis for defining numerical values proper to detectors and coincidence counters. The major shortcoming of this approach is that it treats free particles, but not interactions, or the standard model. There is also a mathematical difficulty that admits of various solutions. The point of departure for the algebraic approach is the Stone-von Neumann theorem. Quantum commutation relations generate the structure of a Hilbert space in a way that is unique up to a unitary transformation. This does not hold for the infinite dimensional representations that QFT uses. Nevertheless, defenders of AQFT hope that these difficulties can be overcome without compromising the integrity of the theory. The chief complaint that members of the AQFT community lodge against mainstream LQFT tradition is that the theory is mathematically unsound.

When one is concerned with interpreting, rather than doing, physics the methodological and/or mathematical consistency are helpful constraints. Creative advances, however, tend to involve hypotheses that break established constraints. Lorentz developed his eponymous equations by successive piecemeal adjustments of order (v/c), $(v/c)^2$ (the contraction hypothesis), and by introducing two different sets of mathematical transformations: one to reduce electrodynamic problems to electrostatic problems; and a second to reduce the optics of moving bodies to bodies at rest relative to the stationary ether. This is a model of anabatic methodology. Einstein simply postulated the invariance of the speed of light and the invariance of the laws of physics and then deduced the same equations. The components of the standard model, electroweak unification and quantum chromodynamics, were based on postulates not justified either by an anabatic methodology. The formulation of the standard model does not comply with the norms of mathematical consistency considered as necessary conditions for the acceptability of a formal theory. Yet, in terms of scope and precision the standard model is the most successful theory in the history of science. It is capable, in principle, of handling the particles, and all the basic interactions, involved in strong, weak, and electromagnetic interactions. For our purposes we do not need the technical details of this model, which I have not mastered, but only two basic aspects. The first is ontological. The family of particles proper to the standard model is a permanent part of physics. As a theory of matter, it is essentially immune to revision by any foreseeable advances in physics.[28]. The second point is epistemological. Rather than judging the standard model by *a priori* norms of what a formal theory should be, it is more helpful to use the standard model as a guide in setting norms for what a *physical* theory should be. Here there are two aspects we will focus on. Local gauge theory is the distinctively new feature of the standard model. The renormalization program gives it the consistency proper to a physical theory. After presenting the basic ideas in a qualitative way we will add a bit of flesh to the bare bones.

We have already considered external symmetries proper to the Poincaré group. These include symmetries under rotation. The trick here is to extend rotational symmetry from external to internal degrees of freedom. Heisenberg introduced isotopic spin space as a simple device for treating protons and neutrons as different states of nucleons. Talk of the z-component of a nucleon's isotopic spin was treated as a metaphorical extension of particle spin. Thus, the different spin components of atomic electrons with the same n and l quantum numbers may be degenerate until a magnetic field is turned on to cause an energy splitting. The fiction was that the energy differences between protons and neutrons would vanish if the electrical field were shut off. This is fictional, because the proton's electric field is internal. There was no *a priori* reason to expect that rotational symmetry could be applied to isotopic spin space. Local gauge symmetry is just such an extension, for isotopic spin space in electroweak unification, and for color space in quantum chromodynamics.

The general program of renormalization supports the concept of *effective theories*. The basic idea is that theories in atomic and particle physics apply to ranges characterized by values of energy or distance. The correlation is important. Intuitively one might think that high energies would overwhelm smaller energies, as they do with competing radio stations or track teams. In the theories we are considering higher energy interactions are correlated with smaller interaction lengths. The basic ideas may be illustrated by fig. (1). One point about the table should be noted. The standard custom, which we will generally follow is to use natural units ($\hbar = 1,\ c = 1$), so that energy and momentum are both measured in mass units. In the chart we have energy in electron volts, rather than the standard Mev, to relate to later discussions of reductionism as well as particle physics.

Interaction Energies



The boxes correspond in a rough fashion to specialized fields that rely on different presuppositions. A theory at a particular level accepts input parameters that should be explained at a deeper level. Thus chemistry and atomic physics overlap at the energy level proper to valence electrons. Chemists generally presuppose atoms and molecules with a mass, spatial configuration, and special properties for valence electrons, e. g., to explain covalent bonding. The energy states of inner electrons, for multi-electron atoms, and the nucleus are not considered. Consider the NRQM treatment of the hydrogen atom. This takes as input parameters the mass and charge of the proton. For more detailed calculations, e.g. of hyperfine splitting, the magnetic moment of the proton is used. However, it is never necessary to consider the quark-gluon structure of the proton. Chemistry and atomic physics remain effective theories on their proper energy levels, totally shielded from modification due to advances at a much deeper level, e.g.,the standard model. Most searches for extraterrestrial intelligence reasonably presuppose that a reasonably advanced civilization would know the periodic table of elements, as well as the basic law of arithmetic. An advanced civilization should also recognize measurements of length, time , and mass in Planck units.

We have been considering theories proper to adjoining or overlapping energy levels. The situation is much clearer for widely separated levels. A study of ocean currents treats water as a continuous fluid. An effective theory of fluid flow is so far removed from its ultimate base that it is compatible with, and accordingly supplies no information about, its ultimate constituents. The equations of fluid flow can be adapted to fit collections of water molecules, the flow of money in banking systems, the migrations of peoples over time, or information in a computer. In terms of orders of magnitude the separation of the standard model from the length characterizing string theory and GUT theories is greater than that between ocean currents and hydrogen molecules. Whether the ultimate theory is a string theory or something different, any relativistic quantum theory at accessible levels will look like a field theory (Weinberg, 1995, p. xxi). The general principle is that a theory can be regarded as an effective theory up to a proper high-energy cutoff. Above that level new physics is needed. This gives strong support to the contention that the standard model is essentially immune to revision by further advances in physics. Such advances may explain the parameters proper to the standard model. However, they will not dissolve the table of particles and properties of the standard model.

4.1 Local Gauge Invariance

To get at the crucial feature of gauge field theory in its simplest form, we will begin with a classical formulation of electrodynamics and the non-relativistic Schrödinger equation. The electrical field strength, **E**, and the magnetic flux density, **B**, may be expressed in terms of the vector potential, **A**, and the scalar potential, V, as

$$\mathbf{E} = -\nabla V - \partial\mathbf{A}/\partial t, \quad \mathbf{B} = \nabla\, x\, \mathbf{A} \tag{20}$$

If we introduce a gauge, f such that $\mathbf{A}' = \mathbf{A} - \nabla f$, $V' = V + \partial f/\partial t$, then the values of **E** and **B** remain the same. This is a global gauge transformation, applying to all of space. It is the gauge transformation Schwinger introduced through his adiabatic methodology.

The phase of a wave function has a peculiar status. The phase is not measurable and does not enter into the calculation of probability densities, since $P = \int \psi^* \psi d\mathbf{x}$. However, phase differences have empirical consequences. Consider the *local* phase transformation,

$$\psi(\mathbf{x},t)' = e^{-\imath\theta(\mathbf{x})}\,\psi(\mathbf{x},t). \tag{21}$$

This is local in the sense that the value of $\theta(\mathbf{x})$ can be different for different positions. To relate this to non-relativistic quantum mechanics as well as electrodynamics, use the Schrödinger wave equation,

$$-1/2m\,\nabla^2\,\psi(\mathbf{x},t) \;=\; \imath\partial\psi(\mathbf{x},t)/\partial t. \tag{22}$$

If in eq. (22) we substitute $\psi(\mathbf{x},t)'$ then we get

$$-1/2m\,\left[\nabla^2(-\imath\nabla\theta\right]\,\psi e^{-\imath\theta(\mathbf{x},t)}] \;=\; \imath\,[\partial/\partial t \;-\; \imath\partial\,\theta(\mathbf{x},t)/\partial\,t]\,e^{-\imath\theta(\mathbf{x}}. \tag{23}$$

This definitely does not have the same form as eq (22). However, we may supplement eq. (21) with the local electromagnetic gauge transformation,

$$\mathbf{A}' = \mathbf{A} \,+\, 1/q\,\nabla\theta(\mathbf{x}),\;\; V' \;=\; V\; - 1/q\,\partial\,\theta(\mathbf{x})/\partial\,t. \tag{24}$$

For a particle of charge, q, the conjugate momentum is $\mathbf{p} \to \mathbf{p} - q\,\mathbf{A}(\mathbf{x})$. The standard quantization procedure is to replace $\mathbf{p}$ by $-\imath\,\nabla$. So,

$$-\imath\,\nabla \to -\imath[\nabla \;-\; \imath q\mathbf{A}(\mathbf{x})] \;\equiv\; -\imath\mathbf{D}. \tag{25}$$

D is the covariant derivative. When this is substituted for the ordinary derivative and the two sets of phase changes are introduced, then the transformed Schrödinger equation has the same form as the untransformed equation.

This covariant derivate gives the coupling between a classical electromagnetic field and a charged particle. The standard model unites the Weinberg-Salam model of electroweak interactions to the SU(3) color model of strong interactions. Here, the covariant derivative can be written in symbolic form as:

$$\partial/\partial x_\mu \;\to\; D/Dx_\mu \;=\; \partial/\partial x_\mu \;-\; \imath g/\hbar\,L_k\,{A_\mu}^k, \qquad \text{where} \tag{26}$$

L_k are the generators of the gauge group, the ${A_\mu}^k$ are the gauge fields, and g is the matching coupling constant. The stagus of local gauge theory should be emphasized. Schwinger's adiabatic method leads to a universal gauge, not a local gauge. Both AQFT and SQFT take local observables as basic. Using the spatio-temporal location of the measuring apparatus as an anchor extends this to further observables. Local gauge symmetry is not an observable. The 'local' implies that each particle has its proper space-time location. This is not only independent of the measurement apparatus as an anchor, it can also be detached form the conceptual foundation supporting this anchor, 4-dimensional space-time. Gauge theory, and the standard model it supports, are methodologically inaccessible to AQFT and SQFT. Yet, the standard model is an unprecedented success, the only theory that covers all basic particle interactions. It covers all basic interactions: hardron-hardron, hardron-lepton, and lepton-lepton, and fit all empirical results until the recent (2002) discovery that neutrinos have mass (not allowed by the standard model). All couplings are effectively represented by covariant derivatives. The values of the couplings are adjusted to fit the empirical data. There is no plausible way to reach these couplings by a series of anabatic steps from a measurement basis.

One further aspect should be treated, the relation between symmetries and invariances. We begin with some general relations between measurements, symmetry operations, and conservation laws proper to classical physics and NRQM. If a system is invariant under linear displacement then linear momentum is conserved. This is the momentum proper to an inertial system specified by the measuring apparatus. Absolute measurement is unmeasurable. Similarly invariance under: time translation implies energy conservation; rotation implies angular momentum conservation. These are external symmetries included in the Poincaré group. Local gauge theory extends this general approach in two ways. First, it adapts the machinery developed for external symmetries to internal symmetries. Second, it goes beyond a measurement basis by postulating that symmetry principles apply to functional spaces characterizing internal degrees of freedom. I will indicate how the principles proper to rotational symmetry and quantization are extended to internal symmetries.

Rotations in a plane involve the group of transformations that keeps $r^2 = x^2 + y^2$ invariant. They can be represented by the one-parameter continuous group, $r' = re^{\imath\theta}$, or through the matrix representation $r' = R(\theta)\, r$ where

$$r = \begin{pmatrix} x \\ y \end{pmatrix}, \quad r' = \begin{pmatrix} x' \\ y' \end{pmatrix}, \quad R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

This is the group $SO(2)$. It is the rotational part of the group $O(2)$, which includes inversions. $SO(2)$ is an irreducible representation. For a reducible representation describe the same system in 3-dimensional space as a rotation about the z-axis. The rotation matrix is

$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{27}$$

This can be reduced to 2 components, a rotation matrix in the $x-y$ plane and a 'do nothing' action along z. Any matrix that has the form

$$T = \begin{pmatrix} T^{q_1} & 0 & 0 & \cdots & 0 \\ 0 & T^{q_2} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & 0 & T^{q_n} \end{pmatrix}$$

where T^{q_i} is a rectangular matrix in a space of q_i dimensions and the '$0's$ stand for block matrices of 0's, is reducible to the rectangular blocks.

To relate this to symmetry we note that we can generate the $SO(2)$ group from its infinitesimal elements. Then $\cos\theta = 1$ and $\sin\theta = \theta$, and

$$R(\theta) = \lim_{n\to\infty}\left(1 + \frac{\imath\,\theta}{n}\tau_3\right)^n = e^{\imath\,\theta\,\tau_3}, \qquad \text{where}\ \tau_3 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Instead of limited rotations about the z-axis we may consider general 3-dimensional rotations. This leads to the group $O(3)$ and the sub-group of continuous rotations, $SO(3)$. The infinitesimal generator for this group is

$$R(\theta) \;=\; \sum_{j=1}^{3} \lim_{n\to\infty} \left(1 \,+\, \frac{\imath\,\theta^j}{n}\,\tau^j\right)^n \;=\; e^{\sum_{j=1}^{3}\theta^j\,\tau^j},$$

A Lie group is characterized by topological as well as group properties. In a Lie group there exists a neighborhood of the identity element, e, in which the inverse of any element and the product of any two elements are continuous and continuously differentiable functions of the parameters. The key theorem that Lie developed is that the infinitesimal generators of a Lie group obey the commutation relations

$$[I_j,\, I_k] \;=\; \sum_{l=1}^{r} c^l_{jk}\, I_l, \tag{28}$$

These commutators constitute a *Lie algebra*, where c^l_{jk} are the structure constants. Because the parameters are all continuous and continuously differentiable, one can work out the properties of infinitesimal group elements and then integrate to get finite group elements. For a compact Lie group, or one with a finite volume, any representation is equivalent to a representation by unitary operators. So, only they need be considered. If we follow the Gell-Mann specification of the τ operators

$$\tau^1 \;=\; -\imath\begin{pmatrix} 0 & 0 & 0\\ 0 & 0 & 1\\ 0 & -1 & 0\end{pmatrix} \quad \tau^2 \;=\; -\imath\begin{pmatrix} 0 & 0 & -1\\ 0 & 0 & 0\\ 1 & 0 & 0\end{pmatrix} \quad \tau^3 \;=\; -\imath\begin{pmatrix} 0 & 1 & 0\\ -1 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

These antisymmetric matrices obey the anti-commutation relations

$$[\tau^i, \tau^j] \;=\; \imath\,\epsilon^{ijk}\,\tau^k, \tag{29}$$

where $\epsilon^{ijk} \;=\; 1$ for ϵ^{123} and is completely anti- symmetric. Equation (29) is a simple example of a 3 parameter Lie algebra with the structure constants ϵ^{ijk}.

To facilitate the transition from external to internal symmetries in a complex Hilbert space we should consider how external symmetries are represented in a complex space. Consider the complex object, $w \;=\; x + \imath y$. Rotations in the complex plane are given by the group of unitary matrices, $U(1)$, where $U' \;=\; U(\theta)\,w \;=\; e^{\imath\,\theta} w$. This gives a correspondence between rotation operators defined in real space and unitary operators defined in a complex space.

$$SO(2) \;\sim\; U(1)$$

This may be extended to get the relation between $SO(3)$ and the special unitary group $SU(2)$. $SU(2)$ is represented by the set of unitary $2\,x\,2$ matrices with unitary determinant Any element of this group can be written in the form, $U \;=\; e^{\imath\theta^i\sigma^i/2}$, where the Pauli matrices, σ^i satisfy the relation

$$\left[\sigma^i/2,\, \sigma^j/2\right] \;=\; \imath\,\epsilon^{ijk}\,\sigma^k/2 \tag{30}$$

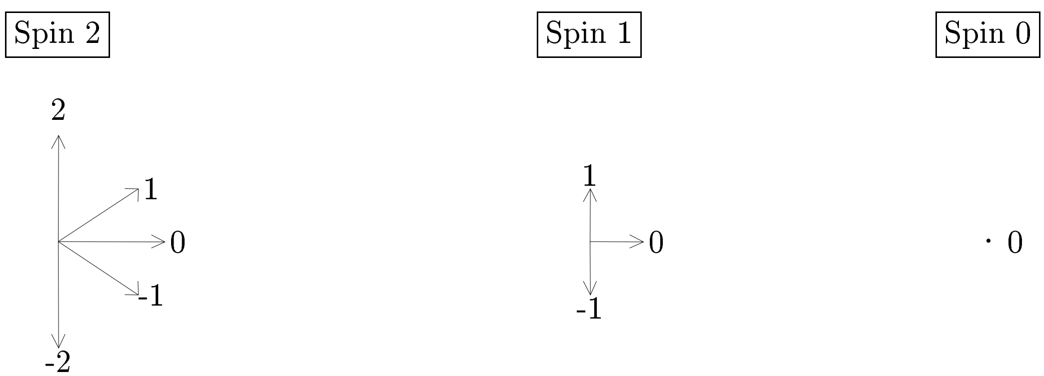
Since equations (29) and (30) define the same Lie algebra we have the correspondence

$$SO(3) \sim SU(2).$$

To see this correspondence in a particular case we note that the rotations, $\mathbf{x}' = \mathbf{O(3)} \cdot \mathbf{x}$ given by equation (27) could also be given by $h' = U\,h\,U^{-1}$, where

$$h(\mathbf{x}) = \sigma \cdot \mathbf{x} = \begin{pmatrix} z & x - \imath y \\ x + \imath y & z \end{pmatrix}$$

Different $SU(n)$ groups supply the basic tools used for symmetry operations in the standard model. The ontology is determined by the combination of three principles: quantum mechanics, relativity, and internal symmetry. From an *a priori* perspective the idea that internal symmetries should play such a role is doubly implausible. The first implausibility is an old one. When Summerfeld introduced the j and m quantum numbers they were bookkeeping devices for spectral lines. Neither he, nor apparently anyone else with the possible exception of Pauli, believed in the reality of space quantization. Then Stern and Gerlach demonstrated that space quantization is real. Consider one aspect of this that gets adapted to $SU(n)$ internal symmetries. Consider joining together 2 spin-1 systems. Each system, considered separately has 3 components along an axis, set by the magnetic field. In quantum numbers, m takes $2j + 1$ values. What of the composite? Diagrams bring out the m components of the 3 different spin state the composite can have.



This can be formulated as a tensor decomposition rule

$$3 \otimes 3 \rightarrow 5 \oplus 3 \oplus 1 \tag{31}$$

The second *a priori* implausibility is the extension of rules like equation (31) to inner symmetries. For external symmetries, the preferred direction is picked out by some physical means, such as the direction of a magnetic field or aspects of a measuring apparatus. How does one set a preferred direction in isospin space or color space? The assumption that compositions in these internal symmetry spaces admit of tensor decomposition and that the components can be accorded physical significance has a profound ontological significance. This can best be seen by beginning with the example that had a pivotal historical significance. The quantum numbers of Q (charge), S (strangeness), and B (baryon number), and I_3 (the projection of isospin along a preferred axis are related by the formula $Q = I_3 + (S + B)/2$.

Gell-Mann introduced the quark hypothesis with the assumptions that baryons are composed of three quarks, mesons are composed of a quark and an anti-quark, that up quarks have a charge of 2/3, down and strange quarks have a charge of $-1/3$, that up and down quarks have isospin values of 1/2, while strange quarks have an isospin value of 0. He introduced the further assumption that the component of isospin along an arbitrary z-axis is $+1/2$ for the up quark and $-1/2$ for the down quark. Then the allowed composition of mesons and baryons led to the tensor decomposition

$$\begin{array}{rl} \text{meson} \quad q\bar{q} \;: & \mathbf{3} \otimes \mathbf{3} \rightarrow \mathbf{8} \oplus \mathbf{1} \\ \text{baryon} \quad qqq \;: & \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \rightarrow \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} \end{array}$$

The known mesons and baryons fit into this systematization. The decuplet had only 9 members, rather than the 10, given by the tensor decomposition. How could symmetry in an abstract isospace supply a basis for predicting a new particle? This hinges on a physical assumption. On a deep level, below the symmetry breaking that accounts for the mass differences, there is only one system. Then, all the allowed states of this system should be realizable, at least in principle. Gell-Mann used the decuplet decomposition for baryons with spin, $j = 3/2$, plus the Gell-Mann Okubo mass relation to predict the existence of a new particle, the Ω^- with an isospin value of -2, a strangeness of -3, and a mass of 1675 Mev. This was in 1962, prior to the 1964 introduction of quarks and based on the phenomenological 8-fold way.

The search for the Ω^- initiated a new relation between experimenters and theoreticians. During the late 1950's and early 1960's experimenters kept discovering new particles and resonance states that supplied challenges for theoreticians. In the new style, theoreticians predicted singular events that could confirm a theory and supplied detailed directions on the type of collisions that might produce the desired results. After Gell-Mann made the prediction at the 1962 CERN conference he had a discussion with Nicholas Samios, who directed high-energy experiments at Brookhaven, and wrote on a paper napkin the preferred production reaction, $K^-p \rightarrow \Omega^- K^+ K^0$. The Ω^- was expected to break down into a cascade of particles.[29]. Samios and his Brookhaven team began the experimental search, developed thousands of bubble-chamber photographs, and even trained Long Island housewives to examine the photos for telltale matched curves. After 97,024 negative results they finally produced a photograph that Samios interpreted as the detection of the Ω^-. A copy of this photo adorns the paper cover of Johnson's (1999) biography of Gell-Mann.

The prediction of particles was based on according symmetry principles an ontological significance. Many physicists, including Gell-Mann and Feynman, were originally reluctant to accept quarks as real. In addition to the novelty of fractionally charged particles there were two basic difficulties. Quarks were not observed and, as fermions, they violated the Pauli exclusion principle. The introduction of color solved the statistics problem and led to quantum chromodynamics (QCD) and the standard model. The proof that non-Abelian gauge theories have the unique property of asymptotic freedom explained why individual quarks could not be observed. The evidence that convinced the scientific community of the reality of quarks stemmed from the Stanford-MIT experiments scattering high-energy electrons off protons. The experimental setup separated elastic, inelastic, and deep inelastic components, while the theoreticians tried to fit the results into a model of the proton as a point mass surrounded by virtual mesons. The deep inelastic component did not fit. In a famous analysis Feynman showed that this component could be explained as elastic scattering from parts of the proton.[30] The parts of his parton model were quickly identified with quarks and gluons. The 1974 discovery of the J/ψ particle led to the charmed quark. When the bottom quark was discovered, symmetry suggested that there must be a corresponding top quark and guided the search. Here, as in RQM, ontological conclusions follow from principles, not formal theories.

Riordan (Riordan, 1992, p. 1292) summarized his historical account with the claim: "Complete conversion of the physics community came in the mid-1970's, in the aftermath of the remarkable chain of discoveries dubbed the November Revolution". This revolution was in 1974. In 1975 both Heisenberg (1975) and Schwinger (1975b, 1975c) still rejected the quark hypothesis. They were probably the only followers of the strict measurement interpretation still active in field theory. Both gave essentially the same reason. 'Particle' is a phenomenological concept. The ongoing process of explaining composites in terms of ever more elementary units should not terminate in particles, but in some more fundamental entities postulated by quantum field theory. The success of the quark hypothesis and the standard model should be taken as conclusive proof that the progress of quantum physics had gone beyond the limits proper to the strict measurement interpretation and its anabatic extension.

The prediction and interpretation of these particles was based on symmetry principles, not on formal theories. This raises the question of the status of the standard model and its two components, electroweak unification and quantum chromodynamics, as theories. The theorists involved in the development of LQFT were not trying to meet the criteria proper to the formal conception of theories. Yet, they did have criteria of acceptability. Paramount among these criteria was the requirement that a theory must supply a basis for calculation and prediction.

4.2 Renormalization and Effective Theories

Renormalization involves complex calculations, which we will skip. It also draws a line separating the formalists from the pragmatists. This is the focus of our concern. For a formalist, a theory should be developed, or at least be recast, as an uninterpreted mathematical formalism that is given a physical interpretation. Using 'pragmatist' loosely for want of a better term, a pragmatist regards a functioning theory as an inferential tool not an uninterpreted formalism. A crucial difference between the two perspectives concerns justification. If the mathematical formulation is treated as an uninterpreted formalism, then the inferential process must have a mathematical justification. A pragmatist is willing to rely on physical justification for key steps. Neither component of the standard model, electroweak unification and quantum chromodynamics, meets basic standards for mathematical rigor. They rely on series expansions that have not been shown to meet the standards of Cauchy convergence, and probably do not converge. A pragmatist has different consistency standards. For a theory to be acceptable it must supply a basis for unambiguous calculations and predictions. Thanks to renormalization, both components of the standard model supply such a basis. Renormalization hinges on the physical interpretation accorded mathematical terms.

Needless to say, I will examine and support the pragmatist perspective beginning with the presuppositions that generate the problem.[31] Classical electrodynamics introduced the idealization of point charges and soon encountered infinities in calculations, such as the self-energy of an electron, that depended on this idealization. Both QED and QFT began with a correspondence principle approach, using and quantizing classical electrodynamics. So, the idealization and problems of point particles was built in. In QED Schwinger was very clear on the physical significance of renormalization. QED is valid for reasonably small distances or reasonably large momenta. For values below some distance cutoff, a, or above some momenta cutoff, Λ, where $a \propto 1/\Lambda$ a new unknown physics must enter. The series expansions involve terms with increasingly higher values of the coupling constant (α in QED) and the energy. Renormalization in QED effectively absorbs the problematic terms in the charge and mass coupling constants and justifies the neglect of high energy terms by the sharply diminishing values of the coupling constants raised to higher and higher powers. Feynman achieved the same effect by a regularization scheme. Regularization involves replacing the actual theory by a modified theory with a built-in cutoff. Feynman's trick was to replace the mass term involved in integrals by $(m^2 - \lambda^2)^{1/2}$, where λ is a fictitious mass assigned to the photon. In both approaches, renormalization involved showing that if one let the cutoff go to 0 (or ∞) the results remained finite.

Regularization and renormalization presented formidable problems in the physics beyond QED. Again, I will skip the details and relate the established results to the ontological issues we are considering. The electroweak theories developed independently by Glashow, Weinberg, and Salam were not taken seriously until 't Hooft established the renormalizability of non-Abelian Yang-Mills theory in 1972. QCD, developed in 1973, presented a different problem. An expansion in terms of increasing powers of the coupling constant led to a divergent series, because of the large value of the strong coupling constant. The assumption of asymptotic freedom supplied an elegant solution to this difficulty. As quarks move closer together the force between them decreases leading to a cutoff at very small distances. The standard model as a theory is given by a Lagrangian with many terms. In terms of gauge properties it is $SU(3)$ (color); $SU(2)$ (weak), and $U(1)$ (electromagnetic). I will summarize aspects pertinent to the issues we are considering.

The Weinberg-Salam theory of electroweak interactions presents a unification of the electromagnetic, $U(1)$, and weak, $SU(2)$ fields. The weak field in not parity conserving and requires a left-handed neutrino. For the unification one needs a left-handed component,

$$L \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L,$$

and a right-hand component

$$R \equiv (e)_R$$

Separate gauge transformations must be introduced for each component under $SU(2)$ and $O(1)$. To get massive vector bosons one must also include spontaneous symmetry breaking and the Higgs mechanism. The standard model adds to these the $SU(3)$ color component for strong interactions. I will ignore such complications and focus on only one point. The covariant derivative used in the standard model can be written in symbolic form as:

$$\partial/\partial x_\mu \;\rightarrow\; D/Dx_\mu \;=\; \partial/\partial x_\mu \,-\, \imath g/\hbar\, L_k\, A_\mu{}^k, \qquad \text{where} \tag{32}$$

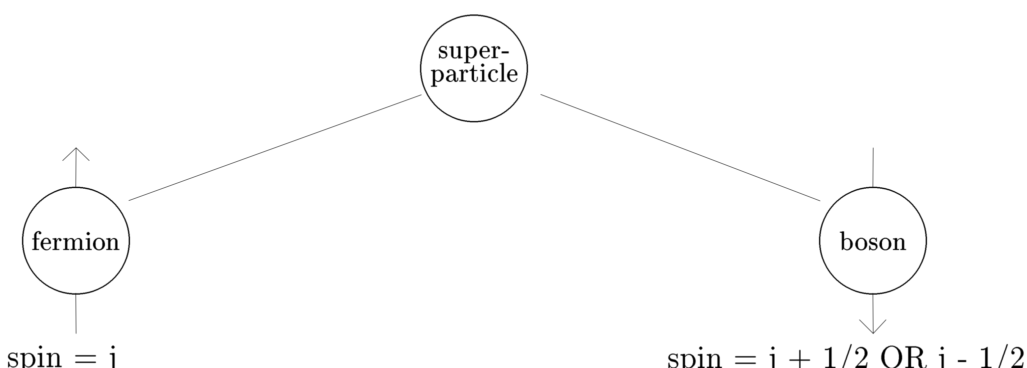
L_k are the generators of the gauge group, the ${A_\mu}^k$ are the gauge fields, and g is the matching coupling constant. This covers all basic interactions: hardron-hardron, hardron-lepton, and lepton-lepton. All couplings are effectively represented by covariant derivatives. This is a renormalizable theory. These couplings are simply postulated and then the coupling constants are adjusted to fit the empirical data. There is no plausible way to reach these couplings by a series of anabatic steps from a measurement basis. This effectively embodies a major step in the program of taking quantum mechanics seriously. The unmeasurable, purely quantum phase component of the wave function is directly related to the local field. Here the space-time framework is also localized, rather than anchored in the space-time framework of the measuring apparatus. The basic particles of the standard model are given in the following table.

Particle	spin	B	L	I	I_3	charge	m_0 (MeV)	antipart.
u	1/2	1/3	0	1/2	1/2	+2/3	5	$\bar{u}$
d	1/2	1/3	0	1/2	−1/2	−1/3	9	$\bar{d}$
s	1/2	1/3	0	0	0	−1/3	175	$\bar{s}$
c	1/2	1/3	0	0	0	+2/3	1350	$\bar{c}$
b	1/2	1/3	0	0	0	−1/3	4500	$\bar{b}$
t	1/2	1/3	0	0	0	+2/3	173000	$\bar{t}$
e^-	1/2	0	1	0	0	−1	0.511	e^+
μ^-	1/2	0	1	0	0	−1	105.658	μ^+
τ^-	1/2	0	1	0	0	−1	1777.1	τ^+
ν_e	1/2	0	1	0	0	0	$< 1x10^{-8}$	$\overline{\nu}_e$
ν_μ	1/2	0	1	0	0	0	< 0.0002	$\overline{\nu}_\mu$
ν_τ	1/2	0	1	0	0	0	< 0.02	$\overline{\nu}_\tau$
γ	1	0	0	0	0	0	0	γ
gluon	1	0	0	0	0	0	0	$\overline{\text{gluon}}$
W^+	1	0	0	0	0	+1	80400	W^-
Z^0	1	0	0	0	0	0	91187	Z

Here B is the baryon number and L the lepton number and there are three different lepton numbers, one for e, μ and τ, which are separately conserved. I is the isospin, with I_3 the projection of the isospin on the third axis. The anti particles have quantum numbers with the opposite sign except for the isospin I. In addition to these basic particles there are hypothetical particles postulated by the standard model. The two most significant are the Higgs particles, postulated to confer mass on the W and Z bosons, and the axion, postulated to explain CP violating terms in QCD. Neither has yet been observed. The axion is a candidate for the dark matter astronomers have inferred.

The novel idea that the value of the coupling constant is a function of distance received theoretical support with the idea of a renormalization group, developed by Wilson and others in condensed matter physics. The idea of running (or variable) coupling constants initially seems counter-intuitive. For almost one hundred years α, the fine structure constant, has been regarded as one of the fundamental *constants* of physics. Calculations of increasing accuracy led to an established result, $\alpha = 1/137.03599911$. To see how this 'constant' could be treated as a variable we recall its definition, $\alpha = e^2/2hc\epsilon_0$. Ideally, a direct measurement of α might be made by bringing two electrons increasingly close together and measuring the strength of their interaction, the e^2 term in the definition. In practice, one relies on high energy scattering experiments. In QFT a charged particle is represented as a bare charge surrounded by a cloud of virtual pairs, the loops in the Feynman diagrams. The distinction between bare and clothed particles plays a basic role in renormalization. If this conception is valid, then electrons at very close distances would penetrate each other's virtual clouds and experience an electrical force stronger than that experienced by more distant particles. The virtual cloud has a screening effect. For the strong coupling constant the virtual cloud has an anti-screening effect, because interactions get weaker as quarks get closer. This hand-waving physical argument can be given a more precise mathematical expression. Thus, the strong-coupling constant, α_s is expressed as a function of momentum, μ by an equation, $\mu \partial\alpha_s/\partial\mu = 2\beta(\alpha_s)$. The solution of this equation involves a series expansion and a constant of integration, whose value must be determined by experiment. This is generally done by determining α_s at some fixed reference scale, such as the mass of the Z boson. Then $\alpha_s \to 0$ as $\mu \to \infty$. (Schmelling, 1997) Here again, the mathematics employed rests on a physical justification.

This idea of running coupling constants supports the idea of *effective theories*. This leads to simplified calculation methods, relying of finite cutoffs in theories while ignoring limiting behavior as cutoffs approach 0 or infinity. It also leads to an appraisal of the physics that lies beyond the standard model. The leading candidate for physics beyond the standard model is supersymmetry. (See Kane, 2000, for a non-technical account). Just as a proton and neutron are regarded as states of a primitive undifferentiated nucleon, so fermions and bosons may be states of some primitive undifferentiated superparticle



All components of the standard model are renormalized. This suggests that it is accurate for calculations up to much higher energy levels. Though it lacks the high precision of QED, the standard model explains a wider class of phenomena and does so with a high degree of accuracy. It also has a basic role in cosmological accounts of the state of the universe immediately after the big bang. There are, nevertheless, compelling reasons for regarding the standard model as an effective theory, a low energy approximation to a deeper theory.

The electroweak component postulates, but does not explain, the spontaneous symmetry breaking that leads to the separation of the electrical and weak components. It requires a massless neutrino. The observed neutrino oscillation requires assigning neutrinos the masses indicated on the preceding table of particles. The hierarchy problem concerns the enormous gap between the energy level of the standard model and that of supersymmetric unification or string theory. Some theories postulate a new physics just a couple of orders of magnitude beyond the standard model. The default position is that there is no new physics between the standard model and the level of supersymmetric unification. Detection of Higgs particles should help to resolve these disputes.(See Pokorski, 2005) The significance of this for running coupling constants is given by Wilczek's diagrams.

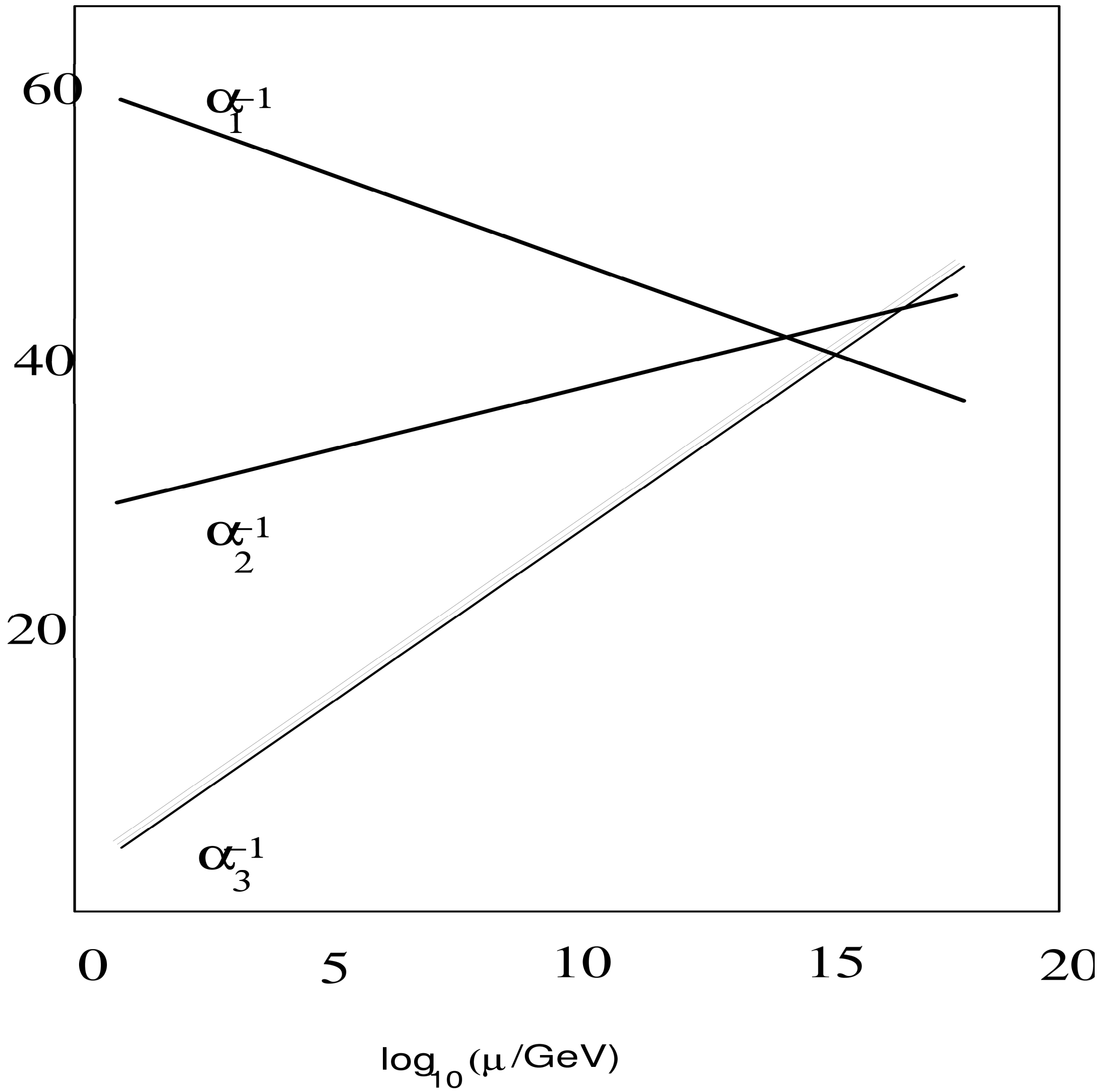


Figure 2: Unification without supersymmetry

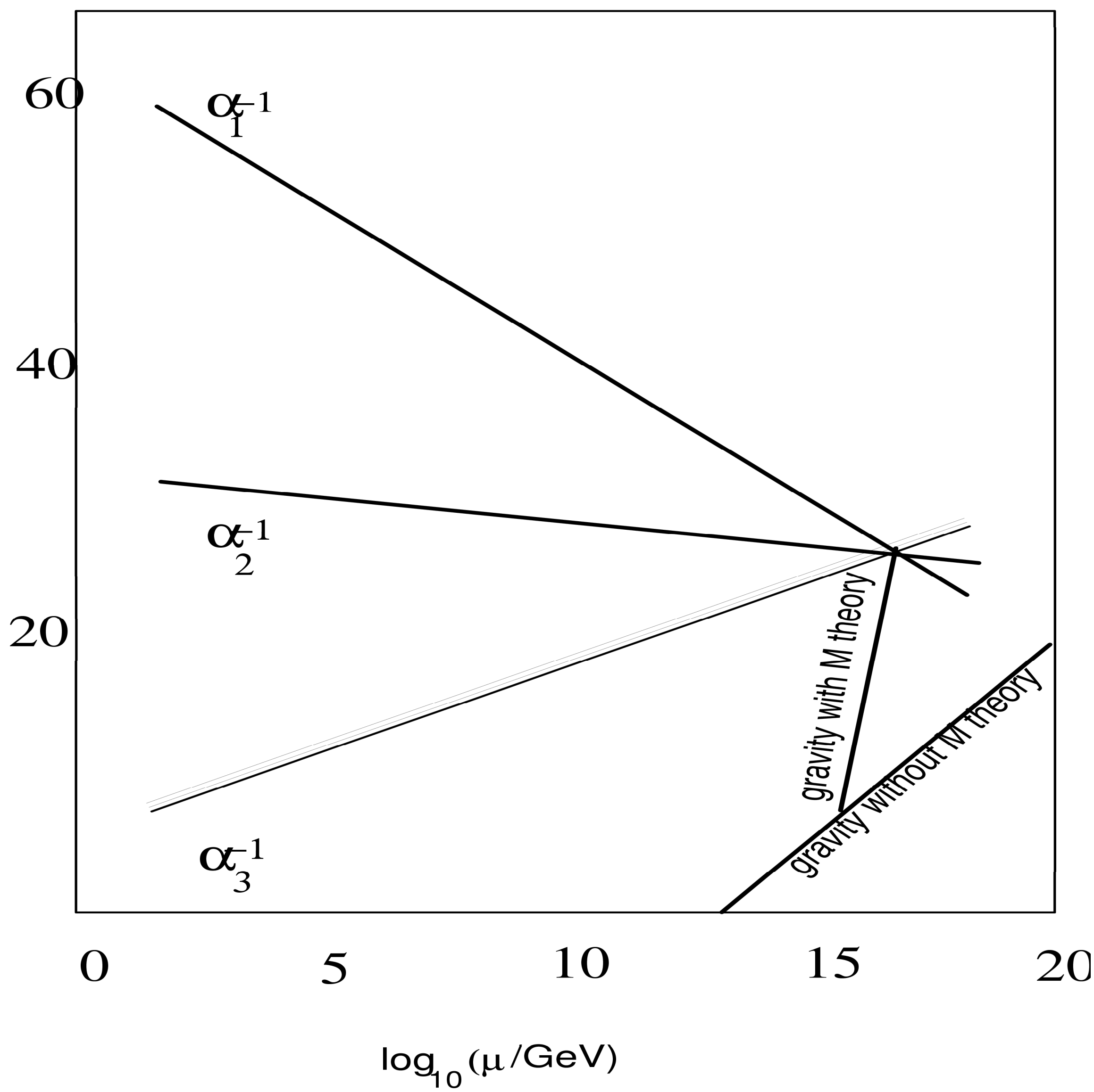


Figure 3: Unification with supersymmetry

Fig. (2) shows the near convergence of the strong (α_3), electromagnetic (α_1), and weak (α_2) coupling constants near an energy level of 10^{15} GeV (or 10^{24} ev on our chart, Fig. (1)). Fig. (3) shows a much sharper convergence at a somewhat higher energy level with the assumption of supersymmetric particles. Witten claims that the M version of string theory supports the conclusion that the gravitational coupling constant also converges to this point. (See Greene, p. 363) I have included this in Fig. (3) as a bit of extra information. However, I will make no further use of string theory.

Physics at this deep level would not change the standard model or its list of basic entities. It should explain some of the parameters that are presupposed in the standard model. With this background we can return to the issue of the relation between theories and ontology. The tension between a formal and an informal interpretation of theories has been a feature in the development of physics for over two hundred years. Lagrange boasted about making mechanics a part of analysis. Laplace countered with what he called 'mathematical physics', using mathematics as a tool for working out the implications of physical hypotheses, while ignoring the mathematical rigor that contemporary mathematicians were beginning to stress. In his *Treatise* Maxwell labored mightily to clarify the physical assumptions behind his equations. Hertz later decreed that Maxwell's theory is Maxwell's set of equations. This tension had a bearing on the origins of quantum mechanics. Both Pauli and Heisenberg did graduate work under Sommerfeld at Munich and then split their time between Götingen, where Hilbert's formalism was a dominant influence, and Copenhagen, where Bohr stressed a physics more closely related to experimental reasoning than to mathematics. Both decisively opted for Bohr's approach. As noted, the tension continues. Lagrangian field theorists quip that the contribution of algebraic field theory to physics is smaller than any pre-assigned number, ϵ. The axiomaticians counter that the only mathematics Lagrangian theorists need is a rudimentary knowledge of the Greek and Roman alphabet.

Philosophers in the foundationalist tradition have put an ontological spin on this clash. The operative assumption is that only formal theories supply a basis for settling ontological issues. Historically, the formalization of functioning theories has made only a negative contribution to ontology. The formalization of classical mechanics by Euler, Lagrange, and others eliminated the foundational role of Newtonian corpuscles. Hertz's deontologizing of electrodynamics suppressed Maxwell's arguments for the reality of displacement. In terms of positive contributions to ontological issues the formalist tradition has a batting average close to 0.00. In the particle physics just considered ontological conclusions hinged on the loose unification of principles in an informal theory. RQM coupled the principles of quantum mechanics and relativity to reach the conclusion that for every Fermi-Dirac particle there is a corresponding anti-particle. QED took quantum mechanics seriously and led to the acceptance of virtual processes given by Feynman graphs. The Lagrangian QFT we have been considering coupled the principles of quantum mechanics, relativity, and locality to get the particles proper to the standard model. None of these theories ever received a proper development as a formal theory. Suppose, however, that this could be done, that algebraic QFT could be developed in a way the included local gauge theories. A necessary condition for the acceptability of such a revision is that it reproduces the essential features of the standard model. No further ontological contribution can be reasonably expected. Supersymmetry might supply the strongest exemplification of this relation between principles and ontology. If the lightest supersymmetric particle is discovered in pending high energy experiments, then the principle of supersymmetry will be vindicated, supporting the conclusion that the whole family of supersymmetric particles exists. String theory supports, but is not entailed by, supersymmetry.

I conclude this survey by returning to the status of this ontology. We have stressed relative ontologies proper to the level of atomic physics and to the standard model. These are functional ontologies. To analyze and interpret experimental data and the pertinent Feynman diagrams it is necessary to assume the particles proper to the standard model. Experimental analysis in particle physics revolves around collision experiments. Experimenters almost never observe the particles the theory predicts. They observe the end products of complex reactions occurring over extremely small time scales. The experimental inferences from the detected to the originating particles presuppose the essential features of the standard model. It does not presuppose that either class of particles are the ultimate constituents of matter. Nor does it rely on any philosophical criteria to distinguish objectively real particles from hypothetical particles. In this sense the ontology of the standard model is an analytic ontology. It is a functioning presupposition of the language used in the discourse between theoreticians and experimenters.

Notes

[1]The classical account of theories as modular units is Darden and Maull.

[2]A summary account of the role of language in classical physics is given in MacKinnon, 1992.

[3]These earlier developments are covered in Hoddeson *et al* 1997. The changing relations between experimenters and theoreticians is treated in Pickering, 1984, 1995, and in Galison, 1987, and Giere, 1988.

[4]The term stems from Shimony (1993), Vol. I. The idea is developed in Bitbol (2001) and Grinbaum (2004). This is essentially a relativized version of the common sense idea that reality as it exists objectively causally determines our knowledge of reality.

[5]In some contexts it is important to distinguish a passive transformation, changing the coordinate system, from an active transformation, moving the system while retaining the coordinate system. A passive transformation leaves the system unchanged.

[6]The original paper was Wigner (1939). A more qualitative summary is given in Wigner (1967), pp. 53-62

[7]The classical account of the role of material inferences is that given by Wilfrid Sellars in many of his essays. The most detailed and most confusing is Sellars (1963).

[8]I am indebted to a conversation with Don Howard for a clarification of this point. See Howard, 1994,and undated. Heisenberg's defense of Copenhagen over hidden variables is given in Heisenberg, 1958, chap. 7.

[9]The most detailed and insightful exposition of Bohr's development on these point is Catherine Chevalley's long 'Introduction' and 'Glossiare' in Chevalley, 1991. See also her 1994. I have benefited from an extensive correspondence with her on these issues and also from working with Ravi Gomatam on his (1998)

[10]MacKinnon, 1982a, chap. 5. The originating context of Bohr's position is treated in Folse, 1985, chaps. 3, 4; Darrigol, 1992, Part B; Chevalley, 1991, 1993; and Petruccioli, 1991. Petersen (1963) remains the best brief summary of Bohr's philosophical outlook.

[11]These further developments are analyzed in my 1982a, chaps 8,10, 1985, 1994, and 1996.

[12]This interpretation of classical physics is presented in MacKinnon, 2002.

[13]General surveys of this development are given in Preskil (1998) and Keyl (2004). A very helpful semi-technical introductory survey is given by Werner (2001)

[14]The problems of localization of quantum information are analyzed in Griffiths (2002) and in Volvich (2002).

[15]See Busch, Grabowski, and Lahti (1995), and also Fuchs (2001)

[16]The venerable classic is MacLane and Birkhoff (1967). A large number of recent books, such as Murphy (1990) treat C* - algebras.

[17]Fuchs (2001) and Volvich (2002) discuss difficulties with the general program. Smolin (2003) and Grinbaum (pp. 134-155) present objections to the CBH proposal. Halvorson (2003) answers the objections that toy theories can be constructed that fit the CBH postulates but do not yield QM.

[18]The quote is form Schwinger (1993), p. 23). The term 'anabatic' stems from Xenephon's classic, Anabasis, which was still a text for Greek class in my high school days. A more extended survey of Schwinger's development is given in Mehra and Milton (2000), pp. 298-566.

[19]Schweber (1994, pp. 355-369, effectively reproduces the talk. The citation is from 361

[20]His 1970b is a slightly revised version of his 1955 lectures. See Gottfried (1966), 192–213 for a summary and Mehra and Milton, pp. 344-355

[21]Wigner (1963) initiated the use of Stern-Gerlach filters as a conceptual tool. It was adapted by Feynman (1965, Vol. III, chaps 5,6), and by Schwinger (See Scully 1989 and Mehra and Milton, chap. 10).

[22]For standard 1960's QFT I am relying on: Schweber (1961), Bjorken (1964) and Lurie (1968).

[23]Schwinger (1965), p. 282) I am also relying on my own notes from Schwinger's 1959 Brandeis Summer course, "Field theoretic methods".

[24]Schwinger proposed this in a privately circulated paper but dropped it when Rabi told him "They hate it.". (See Ng, 1996, Preface)

[25]See Schwinger (1966), (1968a), (1968b), (1969), (1970b). An evaluative summary is given in Milton (1996) For the treatment of gravitational interactions in source theory see Mehra and Milton, pp. 507-514.

[26]My account is chiefly based on the texts by Kaku (1993) and Weinberg (1995) and on the historical accounts given in Hoddeson (1997) and Cao (1997), Part III, and on various articles. For philosophical appraisals of QFT see Auyung (1995), Brown and Harré (1988), and the symposia papers in PSA98, pp. S466-S522, and PSA00, pp. S209-S234.

[27]My evaluation of this approach is chiefly based on Haag (1992), Redhead and Wagner (1998), Buchholz and Haag (1999),and Buchholz (2000). The axioms used are given in Redhead and Wagner, p. 1, and are analyzed in Haag, Section II

[28]The reasons supporting this evaluation are given in Wilczek (1999, 2000, 2000a, 2002b, 2004)

[29]The experimental search is described in Samios, (1997) The changed relation between experimenters and theoreticians is discussed in Pickering (1984), p. 16, and Galison (1987)

[30]Feynman (1974) has a non-technical summary of these calculations. Feynman replaced electrons scattered off stationary protons by high-energy collisions between protons and electrons moving in opposite directions at relativistic velocities. In this framework the transverse movements of the proton are negligible and the momentum distribution of the backscattered electrons gives the distribution of the charged parts of the proton.

[31]The historical development of renormalization is summarized in Cao, pp. 185-207. See 't Hooft (1997) for the problems involved in developing a renormalized electroweak theory.

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