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**FICTION.** *See* **Genre.**

**FIELD THEORIES.** In physics, the field concept describes the distribution and propagation of effects such as magnetism and gravity through space. Field theories have helped implement the program of unifying the "forces" of nature.

### Forces Propagating in Space

The discovery of a connection between electricity and magnetism is usually attributed to Hans Christian Ørsted (1777–1851), who in the winter of 1819 found that a wire carrying a current deflects a magnet. Subsequent experiments determined the dependence of the effect on the relative distance and orientation between the wire and the magnet. Ørsted had pursued his investigations because of his commitment to *Naturphilosophie* and his belief that "the same forces manifest themselves in magnetism as in electricity" and that the fundamental forces of nature were polar. Ørsted's discovery motivated numerous further investigations, by Francois Arago (1786–1853), Jean-Baptiste Biot (1774–1862), Felix Savart (1791–1841), among others, and particularly by André-Marie Ampère (1775–1836) who formulated the force law describing the interaction between two current-carrying wires. Ampère's guiding assumption was that all electrodynamic phenomena could be understood in terms of the interactions among electric charges and the currents they produce when in motion; a magnet being composed of an aggregate of electric currents.

Michael Faraday (1791–1867), prompted by analysis of Ørsted's and Ampère's investigations and of their theoretical assumptions, carried out a series of perceptive experiments. In 1821 Faraday corroborated that the force on a magnet near a current-carrying wire did not act along the line between the centers of two bodies. Following Sir Isaac Newton's (1642–1727) law of action and reaction, Faraday expected that for every effect of electricity on magnetism there should correspond an effect of magnetism on electricity. Displeased with theories of instantaneous action-at-a-distance, he sought the causes of electric and magnetic effects not only within conductors and magnets, but in the medium around them. He assumed that such effects would take time to propagate through space as "lines of force" that could interact with matter. He came to believe in the reality of these lines of force. In 1831 he found that only a *changing* current in a wire will induce a current in a nearby second wire. He came to believe that the phenomenon of the induction of a current in a wire near another that carried a time-varying current was due to its "cutting" lines of force. He also discovered that as light passes through glass near a magnet, the polarization of light rotates. Having found such connections among electricity, magnetism, and light, Faraday continued to investigate the properties of the field around ponderable bodies. His conceptualization of lines of force and of fields continued to evolve from the early 1830s through the late 1840s. Constant in this evolution was the belief that the forces between two or more electrically charged bodies were mediated by some influence—the field—that was created by each body separately, propagated in space and acted upon the other charged bodies. It is difficult to summarize Faraday's notions because contemporary language uses some of the same words as he used but with different meanings. And since Faraday did not use mathematics to describe his theoretical models, we cannot rely on that technical language to clarify his works, as in the case of later researchers. What is clear is that Faraday's notion of a *field* was entwined with his visualization of it in terms of lines of force.

In the 1840s, William Thomson (1824–1907) began to mathematically analyze Faraday's findings in terms of the deformations of a hypothetical material substance, an "ether." Drawing analogies to hydrodynamics and heat conduction, he applied the Laplace/Poisson equation to electrostatics. He showed how to represent work as spread throughout space, and described the ponderomotive force as the tendency of the field to distribute work. He represented magnetic lines of force by vortices and sought a vortex theory of ether and matter.

James Clerk Maxwell (1831–1879) developed extensively this line of research. Following Faraday, Maxwell showed that the lines of electric current and the magnetic lines were linked in a "mutual embrace." He formulated a theory with differential equations that conveyed the reciprocal embrace of constant field lines, and in 1863, for fields varying in time. The latter resulted in transverse waves in the medium, which Maxwell identified as propagating light waves. Like Thomson, Maxwell sought a mechanical account of the ether. He devised a model consisting of cellular vortices and idle wheels that transmit the motion amongst cells and represent electricity.

In Maxwell's theory, the field, which stored and conveyed energy, was fundamental and its displacements constituted charges and currents. Maxwell's theory showed a close causal connection between the separately existing electric and magnetic fields. Heinrich Rudolph Hertz (1857–1894) experimentally demonstrated the existence of invisible electromagnetic waves. Meanwhile, theorists such as Hendrik Antoon Lorentz (1853–1928) interpreted the source terms in Maxwell's equations as densities of charged particles, called electrons. Lorentz developed a theory in which ether and electrons were fundamental entities. He showed that even inside ponderable bodies, electric and magnetic effects are not merely states of matter, but of the fields within.

## Fields and Subatomic Particles

In 1905, Albert Einstein (1879–1955) disposed of the concept of the mechanical ether. Electromagnetic fields propagated in vacuo with the speed of light in all inertial frames. His special theory of relativity showed that the electric and magnetic fields could be represented by one (tensor) field, such that the effects that appear in a reference system as arising from a magnetic field appear in another system moving relative to the first as a combined electric field and magnetic field, and vice versa. The theory also engendered the conception of space and time as a four-dimensional continuum. To account for gravity as a field effect, Einstein formulated the general theory of relativity in 1915. Using tensor calculus and the non-Euclidean geometry of Bernhard Riemann (1826–1866), Einstein described gravitational fields as distortions of the space-time continuum. Meanwhile, following Maxwell, some physicists attempted to construe material particles as structures of fields, places where a field is concentrated. Einstein was among them, yet in 1905 he had proposed that light is composed of particles, "photons."

In the 1920s, Werner Heisenberg (1901–1976), Erwin Schrödinger (1887–1961), Max Born (1882–1970), and others formulated quantum mechanics. Its instrumental successes suggested the possibility of describing all phenomena in terms of "elementary particles," namely electrons, protons, and photons. The components of atoms were treated as objects with constant characteristics and whose lifetimes could be considered infinite. Protons and electrons were specified by their mass, spin, and by their electromagnetic properties such as charge and magnetic moment. Particles of any one kind were assumed to be indistinguishable, obeying characteristic statistics.

Quantum mechanics originally described nonrelativistic systems with a *finite number of degrees of freedom.* Attempts to extend the formalism to include interactions of charged particles with the electromagnetic field brought difficulties connected with the quantum representation of fields—that is, systems with an infinite number of degrees of freedom. In 1927, Paul Adrien Maurice Dirac (1902–1984) gave an account of the interaction, describing the electromagnetic field as an assembly of photons. For Dirac, particles were the fundamental substance. In contradistinction, Pascual Jordan (1902–1980) argued that fields were fundamental. Jordan described the electromagnetic field by operators that obeyed Maxwell's equations and satisfied certain commutation relations. Equivalently, he could exhibit the free electromagnetic field as a superposition of harmonic oscillators, whose dynamical variables satisfied quantum commutation rules. These commutation rules implied that in any small volume of space there would be fluctuations of the electric and magnetic fields even for the vacuum state, that is even for the state in which there were no photons present, and that the root mean square value of such fluctuations diverged as the volume element probed became infinitesimally small. Jordan advocated a unitary view of nature in which both matter and radiation were described by wave fields, with particles appearing as excitations of the fields.

The creation and annihilation of particles—first encountered in the description of the emission and absorption of photons by charged particles—was a novel feature of quantum field theory (QFT). Dirac's "hole theory," the relativistic quantum theory of electrons and positrons, allowed the possibility of the creation and annihilation of matter. Dirac had recognized that the (one-particle) equation he had devised in 1928 to describe *relativistic* spin 1/2 particles, besides possessing solutions of positive energy, also admitted negative energy solutions. Unable to avoid transitions to negative energy states, Dirac eventually postulated in 1931 that the vacuum be the state in which all the negative energy states were filled. The vacuum state corresponded to the lowest energy state of the theory, and the theory now dealt with an infinite number of particles. Dirac noted that a "hole," an unoccupied negative energy state in the filled sea, would correspond to "a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron" (p. 62). Physicists then found evidence that positrons exist.

Beta-decay was important in the field theoretic developments of the 1930s. The process wherein a radioactive nucleus emits an electron ($\beta$-ray) had been studied extensively. In 1933, Enrico Fermi (1901–1954) indicated that the simplest model of a theory of $\beta$-decay assumes that electrons do *not* exist in nuclei before $\beta$-emission occurs, but acquire existence when emitted; in like manner as photons emitted from an atom during an electronic transition.

The discovery by James Chadwick (1891–1974) in 1932 of the neutron, a neutral particle of roughly the same mass as the proton, suggested that atomic nuclei are composed of protons and neutrons. The neutron facilitated the application of quantum mechanics to elucidate the structure of the nucleus. Heisenberg was the first to formulate a model of nuclear structure based on the interactions between the nucleons composing the nucleus. *Nucleon* was the generic name for the proton and the neutron, which aside from their differing electric charges were assumed to be identical in their nuclear interactions. Nuclear forces had to be of very short range, but strong. In 1935, Hideki Yukawa (1907–1981) proposed a field theoretic model of nuclear forces. The exchange of a meson mediated the force between neutrons and protons. In quantum electrodynamics (QED), the electromagnetic force between charged particles was conceptualized as the exchange of "virtual" photons. The massless photons implied that the range of electromagnetic forces is infinite. In Yukawa's theory, the exchanged quanta are massive. The association of interactions with exchanges of quanta is a feature of all quantum field theories.

QED, Fermi's theory of $\beta$-decay, and Yukawa's theory of nuclear forces established the model upon which subsequent developments were based. It postulated impermanent particles to account for interactions, and assumed that relativistic QFT was the proper framework for representing processes at ever-smaller distances. Yet relativistic QFTs are beset by divergence difficulties manifested in perturbative calculations beyond the lowest order. Higher orders yield infinite results. These difficulties stemmed from a description in terms of local fields, a field defined at a sharp point in space-time, and the assumption that the interaction between fields is local (that is, occurs at localized points in space-time). Local interaction terms implied that photons will couple with (virtual) electron-positron pairs of arbitrarily high momenta, and electrons and positrons will couple with (virtual) photons of arbitrary high momenta, all giving rise to divergences. Proposals to overcome these problems failed. Heisenberg proposed a fundamental unit of length, to delineate the domain where the concept of fields and local interactions would apply. His *S*-matrix theory, developed in the early 1940s, viewed all experiments as scattering experiments. The system is prepared in a definite state, it evolves, and its final configuration is observed afterwards. The *S*-matrix is the operator that relates initial and final states. It facilitates computation of scattering cross-sections and other observable quantities. The success of nonrelativistic quantum mechanics in the 1920s had been predicated on the demand that only observable quantities enter in the formulation of the theory. Heisenberg reiterated that demand that only experimentally ascertainable quantities enter quantum field theoretical accounts. Since local field operators were not measurable, fundamental theories should find new modes of representation, such as the *S*-matrix.

During the 1930s, deviations from the predictions of the Dirac equation for the level structure of the hydrogen atom were observed experimentally. These deviations were measured accurately in molecular beam experiments by Willis Eugene Lamb, Jr. (b. 1913), Isidor Isaac Rabi (1898–1988), and their coworkers, and were reported in 1947. Hans Albrecht Bethe (b. 1906) thereafter showed that this deviation from the Dirac equation, the Lamb shift, was quantum electrodynamical in origin, and that it could be computed using an approach proposed by Hendrik Kramers (1894–1952) using the technique that subsequently was called "mass renormalization." Kramers's insight consisted in recognizing that the interaction between a charged particle and the electromagnetic field alters its inertial mass. The experimentally observed mass is to be identified with the sum of the charged particle's mechanical mass (the one that originally appears as a parameter in the Lagrangian or Hamiltonian formulation of the theory) and the inertial mass that arises from its interaction with the electromagnetic field.

Julian Schwinger (1918–1994) and Richard P. Feynman (1918–1988) showed that all the divergences in the low orders of perturbation theory could be eliminated by re-expressing the mass and charge parameters that appear in the original Lagrangian, or in equations of motions in which QED is formulated, in terms of the actually observed values of the mass and the charge of an electron—that is, by effecting "a mass and a charge renormalization." Feynman devised a technique for visualizing in diagrams the perturbative content of a QFT, such that for a given physical process the contribution of each diagram could be expressed readily. These diagrams furnished what Feynman called the "machinery" of the particular processes: the mechanism that explains why certain processes take place in particular systems, by the exchange of quanta. The renormalized QED accounted for the Lamb shift, the anomalous magnetic moment of the electron and the muon, the radiative corrections to the scattering of photons by electrons, pair production, and bremsstrahlung.

In 1948, Freeman Dyson (b. 1923) showed that such renormalizations sufficed to absorb all the divergences of the scattering matrix in QED to all orders of perturbation theory. Furthermore Dyson demonstrated that only for certain kinds of quantum field theories is it possible to absorb *all* the infinities by a redefinition of a *finite* number of parameters. He called such theories renormalizable. These results suggested that local QFT was the framework best suited for unifying quantum theory and special relativity. Yet experiments with cosmic rays during the 1940s and 1950s detected new "strange" particles. It became clear that meson theories were woefully inadequate to account for all properties of the new hadrons being discovered. The fast pace of new experimental findings in particle accelerators quelled hopes for a prompt and systematic transition from QED to formulating a dynamics for the strong interaction.

For some theorists, the failure of QFT and the superabundance of experimental results seemed liberating. It led to generic explorations where only general principles such as causality, cluster decomposition (the requirement that widely separated experiments have independent results), conservation of probability (unitarity), and relativistic invariance were invoked without specific assumptions about interactions. The American physicist Geoffrey Chew rejected QFT and attempted to formulate a theory using only observables embodied in the *S*-matrix. Physical consequences were to be extracted without recourse to dynamical field equations, by making use of general properties of the *S*-matrix and its dependence on the initial and final energies and momenta involved.

By shunning dynamical assumptions and instead using symmetry principles (group theoretical methods) and kinematical principles, physicists were able to clarify the phenomenology of hadrons. Symmetry became a central concept of modern particle physics. A symmetry is realized in a "normal" way when the vacuum state of the theory is invariant under the symmetry that leaves the description of the dynamics invariant. In the early 1960s, it was noted that in systems with infinite degrees of freedom, symmetries could be realized differently. It was possible to have the Lagrangian invariant under some symmetry, yet not have this symmetry reflected in the vacuum. Such symmetries are known as spontaneously broken symmetries (SBS). If the SBS is global, there will be massless spin zero bosons in the theory. If the broken symmetry is local, such bosons disappear, but the bosons associated with broken symmetries acquire mass. This is the Higgs mechanism.

## The Standard Model and Beyond

In 1967 and 1968, the American nuclear physicist Steven Weinberg and the Pakistani nuclear physicist Abdus Salam independently proposed a gauge theory of the weak interactions that unified the electromagnetic and the weak interactions using the Higgs mechanism. Their model incorporated suggestions advanced by the American theoretical physicist Sheldon Glashow in 1961 on how to formulate a gauge theory in which the weak forces were mediated by gauge bosons. Glashow's theory had been set aside because physicists doubted the consistency of gauge theories with *massive* gauge bosons, and such theories were not renormalizable. SBS offered the possibility of giving masses to the gauge bosons. The renormalizability of such theories was proved by the Dutch physicist Gerardus 't Hooft in 1972 under the guidance of Martinus Veltman. The Glashow-Weinberg-Salam theory (GWS) rose to prominence. Experiments in 1973 corroborated the existence of weak neutral currents embodied in this "electroweak" theory. The detection of the $W^{\pm}$ and of the $Z_0$ in 1983 gave further confirmation. Gauge theory, the mathematical framework for generating dynamics-incorporating symmetries, now plays a central role in the extension of QFT. Symmetry, gauge theories, and spontaneous symmetry breaking are the three pegs upon which modern particle physics rests.

Particles such as protons and neutrons are now understood as composed of "quarks." Quantum chromodynamics (QCD) describes the strong interactions between six quarks. Evidence for the sixth was confirmed in 1995. Quarks carry electrical charge and also a strong "color" charge, in any of three color states. QCD does not involve leptons because they have no strong interactions. It is a gauge theory involving eight massless gluons and the tricolor gauge bosons. The GWS of the weak interactions is a gauge theory involving two colors. Each quark thus carries an additional weak color (or weak charge). Four gauge bosons mediate the weak interactions between quarks. Since the 1980s, successful accounts of high energy phenomena using QCD have proliferated.

This elegant "standard model" does not accord with the known characteristics of weak interactions nor with the phenomenological properties of quarks. Local gauge invariance requires that the gauge bosons be massless, and therefore that the forces they generate be of long range. But actually, the weak force is of minute range and the masses of the $W$ and $Z$ bosons are large. Nor does the model accommodate quark masses. A Higgs SBS mechanism is commonly invoked to overcome such difficulties. Establishing its reality is an outstanding problem.

The work of the American physicist Kenneth Wilson and Weinberg gave support to a more restrictive view: All extant field theoretic representations of phenomena are only partial descriptions, valid in the energy domain specified by the masses of the particles that are included, and delimited by the masses of the particles that are excluded. QFTs can be viewed as low energy approximations to a more fundamental theory that is not necessarily a field theory. Such reconceptualizations have led to a hierarchical structuring of the submicroscopic realm with the dynamics in each domain described by an effective field theory. Some see it as rectifying the reductionist ideology that gripped physics. Others pursue the possibility of a more global and symmetric unification than provided by the standard model. String theory is the only extant candidate for a consistent quantum theory to incorporate general relativity and yield a finite theory. The finiteness of the theory is the result of the fact that its fundamental entities are not point-like, but string-like, and space-time is not limited to four dimensions. Particles are then conceived as the quantum states corresponding to excitations of the basic stringlike entities.

Some theorists herald the possibility of a "final theory" that will consistently fuse quantum mechanics and general relativity and unify the four known interactions. This hope was given some credence in 1984 when superstring theory emerged as a candidate to unify all the particles and forces, including gravitation. A newer version in 1994 imagined that there is a single "big theory" with many different phases, consisting of the previously known string theories, among other things. Yet very many questions remain, including how to make contact with the experimental data explained by the standard model. Nor is it clear that such a theory—if formulated—would constitute a final theory and that no lower level might exist.

*See also* ***Physics; Relativity; Quantum.***

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