Proc. Natl. Acad. Sci. USA
Vol. 95, pp. 12776–12778, October 1998
Physics

This contribution is part of the special series of Inaugural Articles by members of the National Academy of Sciences elected on April 28, 1998.

Field theory: Why have some physicists abandoned it?

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Our present-day theory for fundamental processes in Nature—and by this I mean our descriptions of elementary particles and forces—is phenomenally successful. Experimental data confirms theoretical prediction; where accurate calculations and experiments are attainable, agreement is achieved to many—six or seven—significant figures. Table 1 shows two examples. Of course mostly such precision cannot be achieved, neither theoretically nor experimentally. Yet no experiment has thus far contradicted our understanding of the gravitational interactions as described by Einstein's general relativity, nor of the strong nuclear interactions, nor of the electromagnetic and radioactivity-producing weak interactions that are now collected into the Glashow–Weinberg–Salam "standard model." (A hint of physical phenomena beyond the standard model has recently been provided by experimentalists announcing the discovery of a neutrino mass, which is not predicted by the standard model. But if this much-anticipated result is independently confirmed, it can then be fitted very easily into a straightforward extension of the present-day model.) The strong and electro-weak theories make use of a quantum mechanical description, whereas classical physics suffices to account for all known gravitational phenomena.

The theoretical structure within which this success has been achieved is local field theory, which offers physicists a tremendously wide variety of applications; it is a language with which physical processes are discussed and it provides a model for fundamental physical reality, as described by our theories of strong, electro-weak, and gravitational processes. No other framework exists in which one can calculate "so many phenomena with such ease and accuracy" (L. P. Williams, personal communication).

Arising from a mathematical account of the propagation of fluids (both "ponderable" and "imponderable"), field theory emerged over 100 years ago in the discussion within classical physics of Faraday–Maxwell electromagnetism and soon thereafter of Einstein's gravity theory. Schrödinger's wave mechanics became a bridge between classical and quantum field theory: the quantum mechanical wave function is also a local field, which when "second" quantized gives rise to a true quantum field theory, albeit a nonrelativistic one. Quantization of electromagnetic waves produced the first relativistic quantum field theory, which when supplemented by the quantized Dirac field gave us quantum electrodynamics, whose further generalization to matrices of fields—the Yang–Mills construction—is the present-day standard model of elementary particles. This development carries with it an extrapolation over enormous scales: initial applications were at microscopic distances or at energies of a few electron volts, whereas contemporary studies of elementary particles involve 10^{11} electron volts or short distances of 10^{-16} cm. The "quantization" procedure, which extended classical field theory's range of validity, consists of expanding a classical field in normal modes and taking each mode to be a quantal oscillator.

Table 1. Comparison between particle physics theory and experiment in two very favorable cases

Helium atom ground state energy (Rydbergs)	
−5.8071394 (14)	Experiment
−5.8071380 (5)	Theory
Muon magnetic dipole moment	
2.00 233 184 600 (1680)	Experiment
2.00 233 183 478 (308)	Theory

Field theoretic ideas also reach for the cosmos through the development of the "inflationary scenario"—a speculative, but completely physical, analysis of the early universe, which appears to be consistent with available observations. Additionally, quantum field theories provide effective descriptions of many-body, condensed matter physics. Here the excitations are not elementary particles and fundamental interactions are not probed, but the collective phenomena that are described by many-body field theory exhibit many interesting effects, which in turn have been recognized as important for elementary particle theory. Such exchanges of ideas between different subfields of physics demonstrate vividly the vitality and flexibility of field theory.

But in spite of these successes, today there is little confidence that field theory will advance our understanding of Nature at its fundamental workings, beyond what has been achieved. Although in principle all observed phenomena can be explained by present-day field theory (in terms of the quantal standard model for particle physics, perhaps slightly extended to incorporate massive neutrinos, and the classical Newton–Einstein model for gravity), these accounts are still imperfect. The particle physics model requires a list of *ad hoc* inputs that give rise to conceptual, general questions such as: Why is the dimensionality of space-time four? Why are there two types of elementary particles (bosons and fermions)? What determines the number of species of these particles? The standard model also leaves us with specific technical questions: What fixes the matrix structure, various mass parameters, mixing angles, and coupling strengths that must be specified for concrete prediction? Moreover, classical gravity theory has not been integrated into the quantum field description of nongravitational forces, again because of conceptual and technical obstacles: quantum theory makes use of a fixed space-time, so it is unclear how to quantize classical gravity, which allows space-time to fluctuate; even if this is ignored, quantizing the metric tensor of Einstein's theory produces a quantum field theory beset by infinities that cannot be controlled.

But these shortcomings are actually symptoms of a deeper lack of understanding that has to do with symmetry and symmetry breaking. Physicists mostly agree that ultimate laws of Nature enjoy a high degree of symmetry, that is, the formulation of these laws is unchanged when various transformations are performed. Presence of symmetry implies absence of complicated and irrelevant structure, and our conviction that this is fundamentally true reflects an ancient aesthetic prejudice: physicists are happy in the belief that Nature in its fundamental workings is essentially simple. However, we must also recognize that actual, observed physical phenomena rarely exhibit overwhelming regularity. Therefore, at the very same time that we construct a physical theory with intrinsic symmetry, we must find a way to break the symmetry in physical consequences of the model.

Progress in physics can frequently be seen as the resolution of this tension. In classical physics, the principal mechanism for symmetry breaking is through boundary and initial conditions on dynamical equations of motion. For example, Newton's rotationally symmetric gravitational equations admit the rotationally nonsymmetric solutions that describe actual orbits in the solar system, when appropriate, rotationally nonsymmetric, initial conditions are posited.

The construction of physically successful quantum field theories makes use of symmetry for yet another reason. Quantum field theory models are notoriously difficult to solve and also explicit calculations are beset by infinities. Thus far we have been able to overcome these two obstacles only when the models possess a high degree of symmetry, which allows unraveling the complicated dynamics and taming the infinities by renormalization. Our present-day model for quarks, leptons, and their interactions exemplifies this by enjoying a variety of chiral, scale/conformal, and gauge symmetries. But to agree with experiments, most of these symmetries must be absent in the solutions. At present we have available two mechanisms for achieving this necessary result. One is *spontaneous symmetry breaking*, which relies on energy differences between symmetric and nonsymmetric solutions: the dynamics may be such that the nonsymmetric solution has lower energy than the symmetric one, and the nonsymmetric one is realized in Nature while the symmetric solution is unstable. The second mechanism is *anomalous* or *quantum mechanical symmetry breaking*, which uses the infinities of quantum theory to effect a violation of the correspondence principle: the symmetries that appear in the model *before* quantization disappear *after* quantization, because the renormalization procedure—needed to tame the infinities and well define the theory—cannot be carried out in a fashion that preserves the symmetries.

Although these two methods of symmetry breaking successfully reduce the symmetries of the standard model to a phenomenologically acceptable level, this reduction is achieved in an *ad hoc* manner, and much of the previously mentioned arbitrariness, which must be fixed for physical prediction, arises precisely because of the uncertainties in the symmetry-breaking mechanisms. Spontaneous symmetry breaking is adopted from many-body, condensed matter physics, where it is well understood: the dynamical basis for the instability of symmetric configurations can be derived from first principles. In the particle physics application, we have not found the dynamical reason for the instability. Rather, we have postulated that additional fields exist, which are destabilizing and accomplish the symmetry breaking. But this *ad hoc* extension introduces additional, *a priori* unknown parameters and yet-unseen particles, the Higgs mesons. Anomalous symmetry breaking also carries with it arbitrariness: the "renormalization scale" of quantum chromodynamics (QCD), which governs interactions between quarks; moreover, we invoke yet-unseen particles, the axions, which remove from QCD a time-reversal-violating angle that otherwise would have an undetermined magnitude. Moreover, the field theoretic infinities, which give rise to anomalous symmetry breaking, prevent the construction of an acceptable quantum gravity field theory, so it is peculiar to rely on them so critically for the viability of the standard model.

Advancing our understanding of the above has been at an impasse for over two decades. In the absence of new experiments to channel theoretical speculation, some physicists have concluded that it will not be possible to make progress on these questions within field theory, and have turned to a new structure, *string theory*. In field theory the quantized excitations are point particles with point interactions and this gives rise to the infinities. In string theory, the excitations are extended objects—strings—with nonlocal interactions; there are no infinities, and this enormous defect of field theory is absent. Not only does quantum gravity exist in the new context, but it appears that some puzzles having to do with black holes can be answered. Moreover, string theory addresses precisely some of the questions that remained unanswered in field theory: dimensionality of space-time cannot be arbitrary because string theory cannot be formulated in arbitrary dimensions; fermions must coexist with bosons because of supersymmetry—a necessary ingredient of string theory, which requires bosons and fermions to be paired in a symmetry transformation; and so on.

Yet in spite of these positive features, until now string theory has provided a framework rather than a definite structure. Although present-day physics should be found in the low-energy limit of string theory, a precise derivation of the standard model has yet to be given. One thinks again about symmetry and symmetry breaking. The symmetries of quantum field theory surpass those of classical physics and require elaborate symmetry breaking mechanisms. The symmetries of string theory again vastly outpace those of field theory, and must be broken by yet-to-be-developed procedures, to explain the world around us.

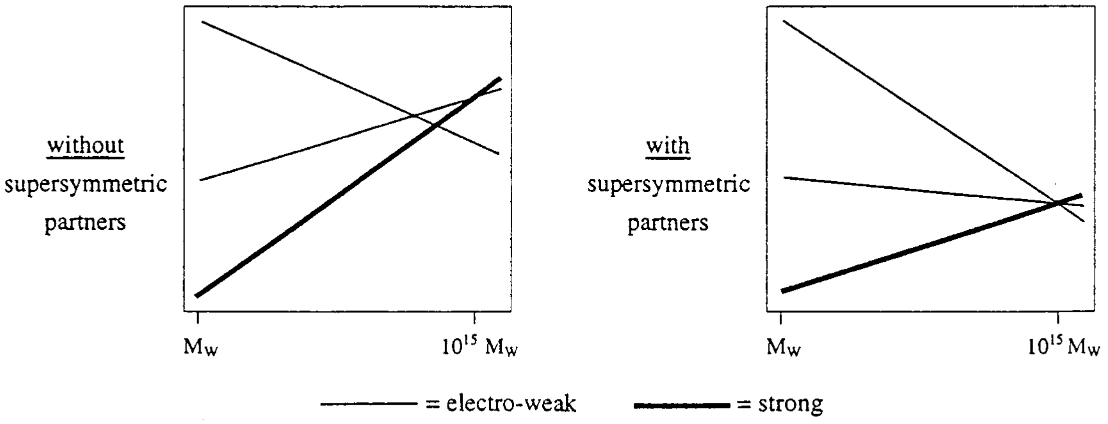

FIG. 1. Schematic plot of (interaction strength)$^{-1}$ in arbitrary units (vertical axis) versus energy in units of $M_W = O(100\text{ GeV})$ (horizontal axis).

Are there any experimental facts—as opposed to theoretical ideas—that support string theory? One can identify only a few. Black holes are accepted as physical entities, and black hole radiance—Hawking radiation—although not yet observed, appears to be a physical concomitant. The process is essentially quantum mechanical, and thus far only string theory gives us a consistent quantum theory of gravity, within which quantal properties of black holes can be calculated. (However, in dimensions lower than the physical 3 + 1, gravity theory can be successfully quantized, and black hole physics can be described, without strings or supersymmetry.)

Support for a different ingredient of string theory—that of supersymmetry—comes from our desire to unify all forces. Unification of the electro-weak and the strong forces, which at present are described by the three separate group theoretical entities, $SU(3) \times SU(2) \times U(1)$, may occur at sufficiently high energies. However, extrapolating present-day data to these high energies shows that the three do not merge into a single entity unless all the particles seen today possess supersymmetric partners (Fig. 1).

Evidently, experimental support is tenuous. It requires extrapolation of 10^{15} to 10^{20} orders of magnitude from present knowledge. Nevertheless, string theory and supersymmetry now consume theorists' work.

A recent compilation by the Institute of Scientific Information of the 1100 physicists with the most cited papers in the last 15 years (http://fluo.univ-lemans.fr8001/1120physiciens.html) is dominated by experimentalists in highly populated fields like condensed matter and materials science. But the list is headed by the mathematicians' Fields medalist Edward Witten, with over 20,000 citations to his writings on supersymmetric string theory that fuel purely theoretical/mathematical speculation. One hopes that in the next millenium experimental data will become available with which we can assess this body of work, and decide whether Nature, as well as the mathematics community, validates these ideas.

On previous occasions when it appeared that quantum field theory was incapable of advancing our understanding of fundamental physics, new ideas and new approaches to the subject dispelled the pessimism. Today we do not know whether the impasse within field theory is due to a failure of imagination or whether indeed we have to present fundamental physical laws in a new framework, thereby replacing the field theoretic one, which has served us well for over 100 years.