might provide cheaper power when used as a bottoming cycle on present plants. The advocates reply that no one will seriously consider investing in an OTEC plant until a true oceangoing prototype is demonstrated.

The OTEC program is scheduled to include three steps leading to a commercial-sized demonstration, now nominally set at 100 megawatts. A 5-megawatt pilot plant is due to be contracted late next year, followed by a 25-megawatt version and finally a commercial prototype, scheduled for installation in 1984. The managers at the Energy Research and Development Administration think that all the problems pointed out by the critics have been recognized and addressed by the program. "We think it is an aggressive program that has set out specific review points based on the experiments necessary before proceeding to larger hardware," says Gronich. Whereas the Academy panel was under the impression that the design of the 100-megawatt system would begin this year, it will actually start in 1980 and "that is a big difference," according to Gronich.

Why is the program moving so rapidly when the burden of the technical criticism is that optimum performance from every subsystem is critical to successful operation? Why have such basic questions as how much power will be available at various distances off shore and whether and at what cost that power can be transmitted back (when undersea transmission experience is limited to rather short distances and minimal depths) not been addressed? Why such urgency to develop at great cost a solar resource which the United States has only in limited supply? Who will own and operate the plants? These questions bother not only utility executives but some solar energy advocates as well. Deploying an OTEC plant will almost certainly require more centralized institutional structures than the present array of independent utilities, which have made it clear that they will not invest in research now and are skeptical about buying the system later.

To keep on its ambitious development schedule, the OTEC program will have to grow rapidly. The longer the task takes the more it will cost. The federal investment in ocean thermal systems could easily begin to match the multibillion dollar investments that have been made in developing nuclear power—an enterprise designed to produce a product of similar size and complexity. The gamble with OTEC is that for technical reasons alone it may provide very little energy.—WILLIAM D. METZ

Elementary Particles: Classical Mechanics to the Rescue?

"Getting back to basics" has been one of the more fashionable ideas recently in several segments of society. A variation of the same theme is making headway in the arcane world of those theoretical physicists trying to construct models of elementary particles.

The problem for theorists attempting to solve equations describing the largest class of elementary particles, the hadrons, is that these nonlinear differential equations are too difficult to solve with existing mathematical tools, even when the equations represent what physicists call the simplest theory with a chance of actually describing the real world. One recently popular approach to this problem has been to study the classical mechanics analog of the quantum mechanical theory. (The resulting equations are not completely classical, however, in the sense that they are still subject to the constraints of special relativity.) The expectation is that classical solutions will provide theorists with the necessary insight to attack successfully the fully quantum mechanical problem.

Investigators following this line of thinking have already found some hitherto unsuspected aspects to their particle theories. Now theorists are hoping that the solution of the classical equations will eventually lead them to quantitative descriptions of the hadrons, including their masses and the strengths of the interactions between them. Whether classical mechanics will ever lead to such successes is problematic, for the history of elementary particle theory is littered with the relics of once promising, but now discarded, theoretical approaches. At present, however, observers seem confident that, even if classical mechanics does not lead directly to experimentally verifiable results, many of the pertinent concepts will survive to be incorporated into future theories.

An extra bonus has been the discovery that the classical equations developed by particle theorists consitute a subset of a larger class of equations that has been studied in detail by mathematicians for altogether different reasons during the last 30 years. What appears as a fruitful cross-fertilization of the two groups of investigators is now under way because it turns out that solution of even the classical equations poses formidable difficulties.

The equations belong to the class of theories called field theories. A field is simply a quantity (scalar, vector, or even tensor) whose values at each point in a coordinate system describe some effect. The electromagnetic field derived from Maxwell's equations, which happens to be a vector field, is probably the most familiar example. That the equations used to model the hadrons might be difficult to solve is perhaps preordained by the complicated name for the type of field theory from which they come: non-Abelian gauge theory. The non-Abelian gauge theories under discussion, which are vector field theories, also go by the name Yang-Mills field theories, after Chen Ning Yang of the State University of New York at Stony Brook and Robert Mills of the Ohio State University, who formulated them in 1954.

The current candidate Yang-Mills field theory is called quantum chromodynamics; the name follows in part because the theory is a generalization of the most successful quantum field theory yet developed, quantum electrodynamics. However, quantum electrodynamics describes only the interactions between electrically charged particles by way of the electromagnetic force, and the charged particles that are most satisfactorily treated are the electron and its antiparticle, the positron.

Elementary particles known as hadrons are so classified because they can interact by way of an altogether different force called the nuclear strong force. The best known examples of hadrons are the proton and the neutron. At very short distances characteristic of the dimensions of nuclei themselves, the strong force dominates all other types of interactions that hadrons can also experience, such as the electromagnetic. The strong force is much more complicated than the electromagnetic, and the resulting quantum field theory is likewise much more complex. Over the years, physicists have successfully combined the results of experiments at ever larger accelerators with studies of the symmetry properties of the equations of theories like quantum chromodynamics to arrive at a scheme for classifying the hadrons into families with certain properties (*Science*, 17 May 1974, p. 782). But the theory has resisted all attempts to solve its field equations.

The computational problems arise from nonlinearities in the equations that are due to the existence of several fields simultaneously. The solution for each field depends on those for all the others. If the couplings between the fields—that is, the degree to which the solutions for each field are interdependent—is large, the equations become strongly nonlinear and difficult to solve.

Quantum electrodynamics nicely illustrates both the origin of the nonlinearities and the ingredients of field theories. These are fields for two kinds of particles. The first type carries an electrical charge whose existence is the origin of the electromagnetic force. The second type, the photon, mediates the interactions between the charged particles—that is, it acts as a carrier of the electromagnetic force. To describe these interactions, it is therefore necessary to solve the equations for two fields whose solutions are interdependent.

Quantum chromodynamics is a considerably more involved proposition. As formulated in 1975 by Harold Fritzsch of the European Organization for Nuclear Research (CERN), Murray Gell-Mann of the California Institute of Technology, and Hans Leutwyler of the University of Bern, there are three kinds of charges, instead of a single electrical charge, that for not entirely whimsical reasons are given the name color charges, hence the name quantum chromodynamics. These abstract "charges" interact by way of the strong force. To account for the interactions between these color charges, it is necessary to have not one, but eight massless particles analogous to photons that carry the strong force, each of which is represented by its own field. A further complexity of the theory is provided by the fact that the hadrons themselves do not carry a color charge—all known hadrons are colorless. Instead, physicists view hadrons as being composed of hypothetical entities called quarks, which do have color and which are also represented by fields.

The color concept was introduced several years ago to account for certain symmetry properties of quarks. Although the concept has nothing to do with visual colors, color charge nonetheless works just like an artist's colors. The three charges correspond to three primary colors. There are two kinds of hadrons. The first, the baryons, are made from three quarks, one of each color, so that they are white or colorless. The second, the mesons, are composed of two quarks; the first quark can be any color but the second is an antiquark having the complementary color. The result is again a colorless hadron.

Perturbation Theory Not Good Enough

Physicists usually tackle problems that seem so intractable by considering the troublesome interactions to be small perturbations. In this way, they can make a series expansion, in the belief that terms in the series involving high powers of a suitably defined coupling constant will be negligible. This procedure has, so far, worked admirably in quantum electrodynamics, but it is entirely unsatisfactory in quantum chromodynamics because the strong force is so "strong."

Although classical mechanics normally is not relevant to highly quantum mechanical entities, such as hadrons, researchers have argued that the strong force is peculiar enough in just the right way that the most interesting interactions between quarks can be approximated by classical mechanics.

By now, classical gauge theories are what Yang of Stony Brook calls an expanding, if unsettled, area of research with a growing list of contributors to its development. The use of classical mechanics offers at least three advantages to theorists. First, although the field equations are difficult, solutions can and have been found. Second, by avoiding perturbation or series expansions, physicists have been able to uncover properties of the fields that are otherwise missed. And, third, it is possible to reintroduce quantum mechanics back into the problem after classical solutions are found in a way similar in spirit to that used by Niels Bohr in his studies of atoms prior to the development of quantum theory. The resulting solutions of the field equations are called semi-classical.

The first thing one calculates in gauge theories are what are called vacuum states of the fields. In the case of quantum electrodynamics, as common sense would seem to dictate, the vacuum is that quantum state in which no photons are present and in which the electromagnetic field therefore has its lowest energy. In quantum chromodynamics the situation is much different. Because of the nonlinearities, according to the classical gauge theory, there are an infinite number of apparently equivalent vacuum states, all of which have the same energy.

The current excitement over classical gauge theories, however, is centered on additional solutions that occur when the equations are formulated in four dimensions. (Theorists, of course, are free to choose any number of dimensions they like.) The fourth dimension is not a spatial dimension but is called imaginary time. For example, Alexander Polyakov and his associates at the Landau Institute for Theoretical Physics, Moscow, found from four-dimensional classical gauge theories that there are new solutions interpretable as events. That is, the energy in the fields is concentrated at a particular point in space and at a particular time. The events, called instantons, are now viewed by physicists as describing transitions from one vacuum state of quantum chromodynamics to another.

Where the quantum mechanics comes back into the picture is in the realization that the vacuum states between which transitions occur are actually states formed by combining the quantum chromodynamics vacuum states. In the picture developed by Roman Jackiw of the Massachusetts Institute of Technology (MIT) and Claudio Rebbi, now at Brookhaven National Laboratory, and Curtis Callan and David Gross of Princeton University, together with Roger Dashen of the Institute for Advanced Study at Princeton, there is a band of these composite vacuum states, each with a slightly different energy, much as the discrete energy levels of an atom become broadened into a band of closely spaced energies when the atoms are brought together in a solid. With the use of the classical instanton solutions, the strength of the transitions between these vacuum states can be calculated. This information constitutes the semiclassical solutions to quantum chromodynamics.

In actuality, the solutions of the semiclassical four-dimensional field equations were preceded by considerable effort on the part of theorists to explore thoroughly comparable equations in two dimensions. According to Dashen, it was the build-up of intuition accumulated from the study of the two-dimensional equations, many of which have exact solutions, that set the scene for the more difficult four-dimensional case. Some of these investigations were by Ludwig Fadeev of the V. A. Steklov Institute of Mathematics in Leningrad, by Jackiw and Jeffrey Goldstone at MIT, by Jean-Loup Gervais, now at the Ecole Normale Supérieure in Paris, and Bunji Sakita of the City College of the City University of New York, and by Andre Neveu of the Institute for Advanced Study.

In the same spirit, important insights were gained from the work of Polyakov and of Gerard 't Hooft of the University of Utrecht in solving classical gauge theory equations (but not those of quantum chromodynamics) in three dimensions. The investigators independently found that there are special solutions that seem to be interpretable as a bizarre kind of particle. The particle interpretation followed because the energy in the field was concentrated at a particular point in space and did not vary with time. Similar solutions to equations in other disciplines, such as fluid dynamics, are called solitons, but the particles found by Polyakov and by 't Hooft had all the properties of magnetic monopoles when one of the fields included was the electromagnetic field. The monopole was quite massive, however, in that it weighed as much as or more than 1000 protons; a particle that heavy could not be seen in any existing or planned accelerator.

Although all this attention on the properties of a vacuum might seem devoted to a hopelessly abstract entity, physicists are interested because there have already been applications of these results to more observable phenomena. A striking example of such application is the use of the new vacuum states and the transitions between them by 't Hooft to explain the problem of a missing particle, known in the jargon of theorists as the U(1) problem.

The essence of the U(1) problem is that a hadron that should exist has never been observed. The origin of the missing hadron lies in the symmetry properties of the equations of quantum chromodynamics. Because the theory is characterized by a high degree of an abstract kind of symmetry, the quarks that combine to make the hadrons ought normally to have the same masses. Real hadrons are such that the quarks must have different masses, and the mechanism describing how these changed masses come about is called spontaneous symmetry breaking. A second manifestation of symmetry breaking is the creation of new particles. In particular, the family of hadrons consisting of pi, K and eta mesons originate this way. The problem is that there should be nine of these mesons rather than the observed eight.

A possible solution to the dilemma was shown by 't Hooft to reside in the possibility of transitions between nonequivalent vacuum states. These transitions reduce the initial symmetry of quantum chromodynamics by just enough to reduce the number of mesons in the family to the eight known by experiment.

More recently, Callan, Dashen, and Gross have outlined a way to explain a problem known as quark confinement; this explanation depends on instantons and semiclassical gauge theory. One consequence of the requirement that all hadrons be colorless is that single quarks do not exist, although a recent experiment has been interpreted to mean that such particles may yet be found (*Science*, 13, May, p. 746). Earlier, Gross and Frank Wilczek of Princeton, and David Politzer, now at Caltech, had shown that quantum chromodynamics is the only realistic field theory that exhibits forces of the type that might explain the inability to produce single quarks. Obtaining a detailed understanding of the mechanism of quark confinement has been called the central problem in quantum chromodynamics.

What the Princeton theorists find is that instantons can exist in three phases as quarks become successively more separated: instantons and anti-instantons bound together (binding corresponds to suppression of the transitions between vacuum states), a dilute gas of instantons, and decomposition of instantons into half-instantons. The third phase is somewhat analogous to a plasma and is also responsible for the confinement. Although one can strain his imagination and try to guess the physical meaning of a half-instanton, the net effect, the investigators argue, is that these entities help generate just the right forces between pairs of quarks and antiquarks to prevent their becoming separated at any time. It is, however, still an argument, not a rigorous proof, and much remains to be done.

Marriage of Mathematics and Physics

To take full advantage of classical gauge theories as approximations of quantum chromodynamics, theorists must spend time as mathematicians—that is, exploring the equations for their own sake and not necessarily for their physical content. As it happens, a good deal of this work has already been done by the mathematicians themselves. In what some observers characterize as a not uncommon coincidence of interests and others as a rather rare occurrence, the mathematical form of the classical gauge theory equations turn out to be the same as that of certain equations in differential geometry dealing with abstract entities known as fiber bundles. For example, the curvature of space in the geometrical theory is analogous to the strength of the field in the elementary particle theory, and the monopole solution to the classical three-dimensional field equations corresponds to a twist in space akin to the twist in a sheet of paper folded into a Moebius strip.

This parallel actually goes back to the early days of this century when Hermann Weyl attempted to construct a geometrical theory to unify electromagnetism and gravity. Much more recently, Yang of Stony Brook and Tai Tsun Wu of Harvard University refocused attention on the parallels between the two types of theories and constructed a dictionary to translate gauge field terminology into that of fiber bundle theory and vice versa.

And on the mathematicians' side, R. S. Ward and Michael Atiyah of the University of Oxford have demonstrated that the existence of gauge fields is equivalent to the existence of a special kind of fiber bundle. Similarly, Atiyah and Nigel Hitchin of Oxford, together with Isadore Singer of the University of California at Berkeley, have used the techniques of global analysis to explore solutions to the equations of physicists' gauge theories.

One of the advantages of the mathematicians' approach is that, by taking what is called a global rather than a local point of view, the geometrical theory avoids certain computational difficulties known as singularities that crop up in physicists' gauge theories. Moreover, the mathematicians have shown the possibility of obtaining a wider class of solutions.

What the relevance of such solutions may be to quantum chromodynamics is still a matter of speculation. Rebbi at Brookhaven thinks that the impact of the mathematicians' point of view will be one of providing insight and new ways of thinking rather than of handing over specific answers on a platter.

There could be a still wider effect of the coalescence of the interests of particle theorists and geometers—whether in the words of Jackiw at MIT the coalescence turns out to be a permanent marriage or a one-night stand—because the geometric point of view is clearly relevant to the intrinsically geometric theory of general relativity. Andrew Hanson, a theorist at the Lawrence Berkeley Laboratory, notes that because of this coalescence and because of a resurgence of interest in finding ways to unify general relativity and quantum mechanics, particle theorists for the first time in a long time are engaging in serious research in gravitational theories. Thus, three once noncommunicating groups may begin working much more closely with one another.

—Arthur L. Robinson