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"Bootstrap": A Scientific Idea?

The place of the bootstrap idea in science is analyzed, from the broad and limited points of view.

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Although the term *bootstrap* has different significance for different scientists, in a uniformly accepted implication self-consistency is accorded a central role. In the broadest sense, bootstrap philosophy asserts that "nature is as it is because this is the only possible nature consistent with itself." In such vague terms the bootstrap idea is much older than particle physics, but within the last decade substantial numbers of physicists have begun serious study of bootstrap notions. Most have been driven to this extremity by an avalanche of unexpected experimental data on strongly interacting nuclear particles (*1*), the hadrons—data which have resisted physics' traditional description of natural phenomena through equations of motion for fundamental degrees of freedom. Some physicists additionally have been motivated by esthetics, finding all proposed alternatives to the bootstrap idea ugly.

In the first part of this article I point out that, in the broad sense, the bootstrap idea, although fascinating and useful, is unscientific. In the remainder of the article I describe a limited bootstrap hypothesis that concerns hadrons only.

We shall find that the scientific status of this partial bootstrap hypothesis is strangely resistant to clarification.

The Complete Bootstrap Hypothesis

Conventional science requires the a priori acceptance of certain concepts, so that "questions" can be formulated and experiments performed to give answers. The role of theory is to provide a set of rules for predicting the results of experiment, but rules necessarily are formulated in a language of commonly accepted ideas. Examples of currently unquestioned prerequisites for science are the following.

1) For macroscopic phenomena, a three-dimensional space and a time that moves in only one direction.

2) The arrangement of macroscopic matter into blobs of reasonably well defined shape and permanency, so that the "isolated system" or "object" concept can be used.

3) The existence of "gentle forces," like electromagnetism, that allow one macroscopic "object" to survive a "measurement" made upon it by another.

4) The existence of objects whose complexity is so great that "consciousness" of measurement becomes meaningful.

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The number of a priori concepts has lessened as physics has progressed, but it would seem that science, as we know it, requires a language based on some unquestioned framework. Semantically, therefore, an attempt to explain *all* concepts can hardly be called "scientific."

Additional insight into the peculiarities of bootstrap philosophy is achieved by remembering that physical theories have always been approximate and "partial." A key discovery of Western culture has been the discovery that different aspects of nature can be individually "understood" in an approximate sense without everything's being understood at once. All phenomena ultimately are interconnected, so an attempt to understand only a part necessarily leads to some error, but the error often is sufficiently small for the partial approach to be meaningful. Save for this remarkable and far from obvious property of nature, scientific progress would be impossible. Current examples of the partial approach in science are a cosmology that ignores quantum effects; a biology that ignores almost all hadrons; a particle physics that ignores gravitation; a natural science that ignores the mechanism underlying consciousness. Supporting the partial approach is the unavoidable error in every experiment. Does it make sense, in other words, to speak of absolute precision in a theory when we cannot conceive of an absolutely precise experiment?

Historically there has been a continuing systematic improvement in the accuracy of experiments and a progressive unification of different areas covered by theory, which have allowed the theories to become more and more accurate. But can this progress of science continue indefinitely? Some scholars, such as Eugene Wigner, argue that at a certain point the question of consciousness must enter the picture, that we cannot indefinitely ignore the observer's role in the nature he tries to understand. To me this conclusion seems inescapable, but such a development lies outside the conventional framework of natural science, which accepts as unambiguous the concept of observation.

Carried to its logical extreme, the bootstrap conjecture implies that the existence of consciousness, along with all other aspects of nature, is necessary for self-consistency of the whole. Such a notion, although not obviously nonsensical, is patently unscientific.

The Hadron Bootstrap Hypothesis

Less immediate is an answer to the question, can a "partial bootstrap" be defined within the scientific context—with certain constraints accepted and certain traditional ingredients, like elementary constituents of matter or a fundamental equation of motion, foregone? In recent times the term *bootstrap* has usually referred to an attempt of this kind, directed at understanding the existence and properties of hadrons while ignoring the existence of photons, leptons, and gravitation.

Let us at once recognize and confront a paradox in this "partial bootstrap" idea. As discussed above, the construction of approximate and partial theories—destined to be superseded by broader and more accurate theories when the accuracy of experiment increases—is the path unavoidably followed by science. All such theories contain some arbitrariness which reflects their incomplete nature. Familiar examples of this arbitrariness are the values used for the mass of the universe in cosmology; the electron mass in atomic theory; the gravitational constant in general relativity; the fine-structure constant in quantum electrodynamics. Each of these is a numerical parameter. Physicists have come to expect and accept such parameters in the temporary role of "fundamental constants," even while knowing that in a future theory these quantities must be derived, not arbitrary. Now, an immediate prerequisite for any conjecture meriting the designation "bootstrap" is the absence of arbitrary parameters, a prerequisite suggesting a final rather than a temporary theory. It is nonetheless apparent that the hadron bootstrap hypothesis at best is incomplete and temporary. Correspondingly it must (and we shall see that it does) possess arbitrary features, even though these do not take the form of numerical parameters. One aspect of this arbitrariness receives special emphasis at the end of this article.

To be scientific, a hypothesis must be susceptible of experimental disproof. Let us proceed next to formulate the hadron bootstrap as precisely as possible and see if disproof is conceivable.

An often heard version of the hypothesis is that all hadrons are "composites" of each other, that none are elementary. Each hadron plays three different roles: it may be a "constituent" of a "composite structure," it may be "exchanged" between constituents and thus constitute part of the force holding the structure together, it may itself *be* the entire composite. A familiar picture qualitatively describes a meson as a baryon-antibaryon composite held together by exchange of mesons, and a baryon as a meson-baryon composite held together by exchange of baryons. Pictures of this type are often used but are unacceptably vague, suffering from dependence on conventional nonrelativistic dynamical language in a situation in which relativity is crucial. The bootstrap mechanism is unavoidably relativistic because the binding energy in the composite must be comparable to the rest-mass energies of constituent particles.

There exists at present no mechanical framework consistent with both quantum and relativistic principles. The chief candidate is local Lagrangian field theory, but countless theoretical studies have suggested insuperable pathology in the concept of interaction between fields at a point of space-time (*2*). An alternative is the analytic S-matrix concept (*3*), in which not only conventional Dirac quantum mechanics but even a meaning for microscopic space-time is abandoned in describing interactions between hadrons.

The basic S-matrix concept is that of momentum, measured, for freely moving hadrons, before and after their collisions with each other. No effort is made to describe the collision itself. Each element of the S matrix describes a particular nuclear reaction and depends on the momenta and spins of the initial and final hadrons participating in the reaction. The experimental definition of momentum and spin involves macroscopic space-time, but no precise meaning need be given to the "position" of a hadron.

Since elements of the S matrix describe all conceivable hadron experiments, ability to predict this matrix would constitute a complete hadronic theory. The essence of the bootstrap conjecture is that three or four general constraints, each strongly supported by experiment, suffice to define a unique S matrix. The first constraint is on macroscopic space-time; it combines the familiar Lorentz (or Poincaré) invariance with the "cluster" requirement that reactions well separated in space-time are independent. The second is unitarity, which combines superposability of free-particle amplitudes with conservation of probability. The third constraint is more subtle and is related to the nonexistence of zero-mass hadrons. Experiments suggest that S-matrix elements are *analytic* functions of the hadron momenta on which they depend. In the absence of zero-mass hadrons there is no bar to analytic continuation to complex values of momentum, energy, and mass, apart from isolated singularities required by unitarity. Among these singularities, simple poles correspond to particles, the pole position determining the particle mass, the residue determining a partial width. ("Complex mass" means that the hadron is unstable, the imaginary part of the mass corresponding to the lifetime.) There also occur various branch points associated with the name of L. D. Landau and related to the possibility that complicated reactions proceed through a succession of simpler reactions. Causality is ensured by the proper location of the Landau branch points (*4*). The S-matrix constraint of "first-degree analyticity" requires postulation of no momentum singularities other than particle poles and Landau branch points. This third constraint has substantial experimental support, although its basis is not as compelling as that for the constraints of Lorentz invariance and unitarity.

The pole-particle correspondence fails to distinguish between "elementary" and "composite" particles, but 10 years ago, in nonrelativistic potential-scattering theory, Tullio Regge identified a connection between composite-particle poles and S-matrix behavior as certain momenta approach infinity. Unitarity demands some such connection for relativistic high-spin hadrons, and S. Frautschi and I conjectured that Regge asymptotic behavior might be used in the relativistic hadron S matrix to *define* "compositeness." Thus a possible fourth S-matrix constraint is the constraint that all poles be Regge poles, a condition sometimes called "second-degree analyticity" because Regge behavior involves analytic continuation in angular as well as linear momenta (*5*). A different term often applied to the same condition is "nuclear democracy." This fourth constraint had little experimental support when it was proposed in 1961, but it has by now acquired respectability. Although there exists no firm logical bar to alternative constraints involving elementary particles without arbitrary parameters, the esthetic principle of "lack of sufficient reason" may be invoked. There seems no "need" for elementary hadrons.

In summary, according to the partial bootstrap hypothesis, observed hadron phenomena correspond to the *unique* Lorentz-invariant, unitary, analytic S matrix containing only Regge poles.

Can we imagine experimental results that would disprove this hypothesis? Two aspects of the hypothesis are potentially vulnerable:

1) Is it really true that the requirements of unitarity and Lorentz invariance, together with first- and second-degree analyticity, suffice to determine one and only one S matrix? This question evidently cannot be tested experimentally because there *is* only one hadronic S matrix in nature. A basis for rejection of the hypothesis could be the mathematical proof that existence of one S matrix satisfying the stated conditions implies the existence of a second, or the mathematical demonstration that *no* such S matrix exists. Such demonstrations would be extremely difficult because of the nonlinear character of unitarity, perhaps as difficult as would be a proof that one and only one solution exists. In any event these questions are mathematical, not scientific.

2) Conceivably, experiments could establish beyond reasonable doubt that certain hadrons are not Regge poles. Recurrence, for example, is a characteristic Regge phenomenon, each particle being a member of an infinite family. The fact that we see only one photon and one electron leads us to believe that these particles are not Regge poles. (They are, of course, not hadrons.) The chief candidate among known hadrons for non-Regge status is the pion, which has an exceptionally small mass and a number of associated unusual properties. No pion recurrences have yet been established. In fact, the pion is sufficiently similar to other hadrons to make non-Regge status unlikely, but this is an experimental, and therefore scientific, issue.

What have quarks to do with the bootstrap? The naive concept of the quark is that of a non-Regge pole—an old-fashioned elementary particle out of which all other hadrons are constructed (*6*)—apparently the antithesis of the bootstrap. If a quark is defined only by its peculiar quantum numbers (for example, charge $e/3$), however, it is by no means obvious that it must be more elementary than the other hadrons. Quarks might also be Regge poles with infinite recurrences, and their discovery would not, per se, destroy nuclear democracy. It would have to be shown that they possess certain exceptional dynamical characteristics. In principle these characteristics could be experimentally ascertained, so the issue is scientific.

Thus there exists at least one possible path for experimental demolition of the hadronic bootstrap: the discovery of non-Regge poles among hadrons. Established universality of Regge poles among hadrons, however, would not convince all physicists that we are dealing with an S-matrix bootstrap. It is often conjectured that, beneath nuclear matter, lies a basic field obeying a simple "master equation" of motion (*7*). Lagrangian models indicate a tendency for hadrons sharing the quantum numbers of such a master field to exhibit "aristocratic" properties, such as not lying on a Regge trajectory, but no general demonstration ever has been given that a master equation precludes nuclear democracy. Since a master field would be inaccessible to direct measurement, one may despair of ever verifying its actuality.

The history of the past 30 years suggests that, regardless of experimental developments, the antibootstrap local-field approach to understanding hadrons will not die but, from lack of encouragement, *may* fade away. What would constitute "lack of encouragement"? This could arise from continuing failure to resolve inconsistencies in the field-theoretical structure, coupled with a demonstration that all significant experimental predictions of local-field models can be achieved within a pure S-matrix framework. (We are already close to such a situation.) Thus, with the passage of time one can conceive a slow evolution—even without the impetus of experiment—to a stage at which most physicists have convinced themselves that local-field theory is inapplicable to hadronic phenomena. If at that point the S-matrix constraints of Lorentz invariance, unitarity, and analyticity still stood, and nothing but Regge poles had been found among hadrons, the bootstrap hypothesis would no doubt command wide support.

Nonetheless, even in this fantasy world, conclusive experimental confirmation of the hadron bootstrap is hard to imagine. A "bootstrapped" S matrix contains an infinite number of poles, and no single one can be completely understood without an understanding of all the others. The traditional scientific technique of identifying a few key experiments whose results can be predicted with precision is unavailable. There is no analog to the hydrogen atom's role in quantum electrodynamics. The absence of arbitrary parameters means that there is no unambiguous base for making predictions.

The lack of a definite starting point for making predictions is so alien to scientific practice as to prevent many distinguished physicists from taking seriously the hadron bootstrap. They conclude, in other words, that we are dealing here with an unscientific idea. This may be a logically correct conclusion, but it is at the same time conceivable that the bootstrap hypothesis is destined to yield an unending series of gradually more precise relationships between different aspects of the hadron S matrix, a series that will asymptotically *approach* complete understanding. A recent example of such a relationship is the so-called finite-energy sum rule (*8*). This sum rule relates high-energy peripheral reactions in a remarkably direct way to low-energy resonances, and shows promise of explaining why low-mass hadrons are roughly classifiable according to irreducible representations of certain Lie groups (*9*). A development plausibly anticipated for the near future is an explanation of unusual pion properties in terms of the small pion mass. Another is an explanation of multiple particle-production at high energy in terms of low-energy two-particle phenomena. There seems no limit to the number and scope of the predicted correlations that can be based on the hadron bootstrap hypothesis. Perhaps a sufficiently "dense" accumulation of successful correlations will come ultimately to be regarded as acceptable verification of the theory.

Conclusion

In closing, let me return briefly to the arbitrariness of the hadron bootstrap. Even without arbitrary parameters or equations of motion, we have presupposed as framework the analytic S matrix, with a number of constraints. The constraint of nuclear democracy may indeed turn out to be nonarbitrary and, correspondingly, superfluous; so also may the constraint of first-degree analyticity. But what about the constraint of Poincaré invariance and the related a priori concepts of momentum, and macroscopic space-time? Can we imagine a more complete bootstrap in which such components would not appear arbitrary?

It is striking that electromagnetism appears essential to the experimental measurement of hadronic momentum, while at the same time guaranteeing some ambiguity for any such measurement. For example, the long-range Coulomb field underlies the existence of macroscopic solids from which measuring apparatus is constructed. The zero photon mass, on the other hand, causes every hadron to be accompanied by an infinite number of soft electromagnetic quanta. Only the small value of the fine-structure constant prevents this infrared phenomenon from completely invalidating the analytic S-matrix description of hadrons. Here we may see foreshadowed a future step in the classic evolution pattern of science, a pattern emphasized at the beginning of this article.

In order to "understand" the origin of an arbitrary and slightly imprecise feature of the partial hadron bootstrap, we shall someday perhaps enlarge the bootstrap. The new framework must be broader and more accurate than the analytic S matrix; more important, the existence and properties of electromagnetism, and indeed of macroscopic space-time, within this new framework may not appear arbitrary.

Such a future step would be immensely more profound than anything comprising the hadron bootstrap; we would be obliged to confront the elusive concept of observation and, possibly, even that of consciousness. Our current struggle with the hadron bootstrap may thus be only a foretaste of a completely new form of human intellectual endeavor, one that will not only lie outside physics but will not even be describable as "scientific."

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