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INTRODUCTION

Physicists usually perceive their discipline's goal as the reduction of nature to fundamentals, and the high-energy arena has correspondingly been dominated by the search for "basic building blocks." Finding the quark[1] is momentarily regarded by many as the ultimate prospective triumph; failure to find some such fundamental entity is equated with frustration. There exists, nonetheless, a 180^{o}-inverted point of view which envisions the absence of fundamentals as the ultimate triumph; this is the bootstrap[2] attitude.

The bootstrapper seeks to understand nature not in terms of fundamentals but through self-consistency, in the belief that all of physics flows uniquely from the requirement that components be consistent with one another and with themselves. No components are supposed to be arbitrary. Now by definition a "fundamental" component is one which is arbitrarily assignable; thus, to a bootstrapper the identification of a seeming fundamental quark would constitute frustration.

The purity of the distinction between fundamentalist and bootstrapper is blurred by the unavoidable inexactness of physical measurement and the parallel finiteness of human intellectual capacity. At any given stage in the development of their science, physicists inevitably deal with an approximate and incomplete description of nature. As the accuracy and scope of experiments increase, a component of nature, which at first appears "fundamental," eventually may emerge in a different light. If we are rationally to discuss the currently perceived quark-bootstrap alternatives, therefore, it must be within some agreed level of approximation.

A natural choice may be based on the distinction between "strong" interactions and the three other recognized categories--electromagnetism, gravitation, and "weak interactions."[3] Physicists often attempt to describe the first category as if the other three did not exist. The tenability of such a view remains unclear, but for the discussion here let us employ the idealization of a flat-space-time world with neither gravitation nor weak interactions. Electromagnetism enters only as a gentle measuring probe which is assumed not to perturb the system. The question then is whether the description of hadrons in such a world forbids or requires a fundamental arbitrary entity such as a quark.

To sharpen the discussion let us accept certain general constraints on the hadron S matrix that are believe to correspond to well-established cause-effect aspects of space-time in the absence of infinite-range forces. These constraints are often summarized as (1) Poincaré invariance, (2) unitarity, and (3) analyticity.[4] The simplest and most appealing version of the hadron bootstrap conjecture supposes that only one possible S matrix is consistent with these constraints and that this unique S matrix approximates actually-observed hadronic phenomena. The fundamentalist viewpoint, in contrast, assumes the general S-matrix constraints to be compatible with an arbitrary assignment of fundamental "entities," such as quarks.

Because of the baffling nonlinear character of unitarity, theorists not only have failed to establish mathematically whether the structure of space-time implies a unique S matrix, but they have left open the possibility that no S matrix can simultaneously satisfy all three constraints. It was from this mathematical dilemma that the hadron bootstrap conjecture originally sprang. The experimentally observed hadron S matrix seems to satisfy the constraints, even though theoretical physicists never have come close to constructing a model possessing all three general properties. If the only consistent S matrix is in fact that seen in nature, the theorists' failure becomes understandable, because observed hadronic phenomena are too complex to be encompassed by any explicit construction of human imagination.

The fundamentalist viewpoint is buttressed by Lagrangian local-field models, patterned on quantum electrodynamics. These models superficially suggest that a variety of arbitrarily designated fundamental particles is compatible with Poincaré invariance, analyticity, and unitarity. Lagrangian models, however, have been defined only through power series expansions--which may not converge. Implicit in the hadron bootstrap conjecture is the belief that no Lagrangian model can lead to a completely satisfactory S matrix.

Would experimental discovery of a particle with quark quantum numbers settle the issue? The answer is no, unless the observed properties of the particle somehow suggested a theoretical model that established the nonuniqueness of the hadron S matrix. In other words, the mere discovery of a particle with quark quantum numbers would not demonstrate that the particle is fundamental. It might simply be the first-seen member of a new branch of the hadron family, all of whose members are uniquely and democratically prescribed by compatibility with the whole.

Would persistent failure to find any quark settle the question? Again the answer is no. Models often have been proposed, albeit not demonstrably satisfying all the general conditions, that contain no elementary particles but which are based on arbitrarily designated fundamental fields.

What hope, then, is there to resolve the issue? The honest answer to this question is unpalatable to particle physicists who dream of the press conference that will announce to the world a dramatic resolution of their quest. No single experiment or theoretical calculation is likely to decide the contest between quark and bootstrap hypotheses. It will take years and innumerable individual developments gradually to swing the balance one way or the other.

Before a consensus is reached, in fact, the issue may well become perceived in a different light from that presented here. Isolation of the hadrons on the basis of an analytic S matrix may become untenable as the range of experiments expands. A broader and less arbitrary framework may be needed. In the final analysis it must not be forgotten that the S matrix depends on the arbitrary concept of space-time. From an ultimate bootstrap point of view, <u>all</u> concepts should be justified by self-consistency, none should be accepted on an <u>a priori</u> basis. At best, therefore, the hadron bootstrap hypothesis represents only a partial bootstrap, and the status of "partial self-consistency" is slippery.

In the concluding section below, prospects for a more complete bootstrap are briefly considered. The central concern of this article, nevertheless, is with strong interactions as an isolated phenomenon.

THE RECENT PAST

I have described in excessively crude terms the unpalatability to most physicists of the bootstrap idea. Many physicists do not require the goal of a press conference, but they do need, for their own satisfaction, the prospect of a major breakthrough within their lifetime. The notion of "breakthrough" is subjective, so it is appropriate here to recall certain past developments in hadron physics as a basis for speculation about the bootstrapper's prospects.

On occasion, hadron physics has exhibited dramatic quality in that a single experiment seemed to play a decisive role in confirming some general principle. The discoveries of the pion and the antiproton are examples. In retrospect, however, we see that the significance of these discoveries could be properly assessed only after many other experiments had followed. Much of the 1947 excitement about the pion was based on the notion that this particle was "fundamental." The real significance lay in supporting Yukawa's idea of a connection between particle mass and interaction "range," a notion that after further work turned out to be extremely general and a prime mover in an epochal hadronic development of the fifties: the recognition of the analytic relativistic S matrix, with its pole-particle correspondence. Also crucial to the analytic S matrix was the association of negative energies with antiparticles ("crossing"), a concept apparently overlooked in S-matrix work during the forties--probably because the generality of antiparticle occurrence was at that time not widely accepted. The discovery of the antiproton in 1954 demolished all skepticism on this score, but acceptance of the analytic S matrix did not immediately follow. Many additional experiments to confirm a variety of Cauchy formulas ("dispersion relations") were needed to build confidence in analyticity, and these high-precision experiments dragged out over many years.

It would be difficult to say at what point in time during the early sixties the accumulated evidence became sufficient to persuade a preponderance of particle physicists that indeed the S matrix is an analytic function, with only those poles and branch points required by causality and(or) unitarity. This realization constituted a "breakthrough" of major proportions, even though no press conference was called. It was a brilliant collective achievement of the high-energy physics community.

The high-energy community is presently immersed in another long-drawn-out effort to verify a conjectured sweeping hadronic principle --that of Regge asymptotic behavior.[5] Once again no single experiment can be decisive; although almost a decade has elapsed since the conjecture of Regge asymptotics began to be discussed, a substantial group of skeptics today remains unconvinced. However, their number is dwindling and it seems not unlikely that at some point within the next few years the generality of Regge hadron asymptotics will become regarded as "established." When and if such a situation comes to pass, another momentous breakthrough will have been achieved.

Discoveries like that of the analytic S matrix and Regge asymptotic behavior occur so gradually as almost not to seem like discoveries, but over a ten- or twenty-year interval the decisive character of such developments can be recognized. Intervals of this order of magnitude still fall within an individual human lifetime, and it is in this spirit that the bootstrap hypothesis should be regarded. It is conceivable that over the period of a decade or so the collective weight of many experiments and many calculations will lead to "acceptance" of some form of bootstrap principle for hadrons.

Would such an eventuality represent triumph or frustration for hadron physics? In the author's view, as the reader by this time will have guessed, the triumph would be of an unprecedented magnitude and would ultimately affect all of physics. The author would find it a crushing disappointment if in 1980 all of hadron physics could be explained in terms of a few arbitrary entities. We should then find ourselves in essentially the same posture as in 1930 when it seemed that neutrons and protons were the basic building blocks of nuclear matter. To have learned so little in half a century would constitute, at least for this human being, the ultimate in frustration.

THE IMMEDIATE FUTURE: SPECULATIONS

Now that the author's heavy bias lies exposed, conjectures about the immediate future of hadron physics are in order. Following, then, are speculations on conceivable developments that might pave the way toward eventual acceptance of the hadron bootstrap idea.

It may come to pass, first of all, that expansion of experiments in scope and precision will reveal intrinsic limitations of certain widely used correlation rules that have arisen from models motivated by fundamentalist notions. A prime example is the set of spectral rules based on quark models.[6] The success of quark-model spectral predictions is, of course, an encouragement to fundamentalists. If, during the next few years, it becomes clear that quark rules cover only a small portion of the full spectrum--in the same sense that the shell-model rules of low-energy hadron physics have only a limited validity--the tendency to assign fundamental significance to quark-model components will fade.

Other rules that may suffer a similar fate include those that assign a privileged position to the pion (PCAC, chiral symmetry)[7] and to the 1^- meson (vector dominance). Although these rules are not immediately related to quarks, they are motivated by fundamentalist-created models and their usefulness tends to perpetuate the fundamentalist viewpoint. Should such rules turn out to be of clearly limited validity, an increasing proportion of hadron physicists may turn elsewhere for a deeper understanding.

Bootstrappers cannot, of course, ignore the partial success of the fundamentalists' models. In the past a typical bootstrap response has been to argue that portions of the analytic S matrix near an isolated pole may be approximately described by ignoring other singularities. For that localized portion of the S matrix, the dominating pole may then appear to be "fundamental." If, in the future, analogous arguments can be found to encompass convincingly all successes of the fundamentalists' models, the case for literal interpretation of the model components will be undermined.

Quark-model successes are not easily explained by a "nearby singularity" mechanism; something much more subtle will be required. The currently most promising bootstrap interpretation of quark rules involves the Veneziano model,[8] whose status in the present discussion is strikingly ambiguous. Some students of the Veneziano model interpret it in bootstrap terms, while others find a conventional fundamentalist interpretation. In any event, it allows quark-model rules to be framed in the language of the analytic Regge-behaved S matrix, without any implication that quarks must exist as particles. Most encouragingly, the Veneziano model suggests a relation between small resonance widths and quark-model rules; amplification of this relation eventually may shift attention from quarks to the origin of small widths.

It is in their attitude regarding the width question that Veneziano-model students sharply differ. Fundamentalists are prepared to accept an arbitrary parameter which determines widths; bootstrappers do not tolerate any such arbitrariness, anticipating that the three general S-matrix constraints will fix particle widths as well as particle masses. The Veneziano-model situation is analogous to that described above for Lagrangian models: Fundamentalists hope that an infinite-series representation of the S matrix will satisfy all constraints, including unitarity, for an arbitrary assignment of certain fundamental Veneziano parameters; success in this endeavor would destroy the hadron bootstrap hypothesis. Bootstrappers correspondingly hope and expect that no such series representation will be found, placidly accepting as insurmountable the failure of the model to satisfy unitarity.

The reader may by now have become impressed by the negative character of the bootstrap idea, with its insistence that no theoretical model can be entirely satisfactory. Since a hypothesis seems unlikely to be verified entirely through the failure of its competitors, what positive steps can be imagined toward verification of the bootstrap notion?

Positive steps may take the form of a limitless variety of partially successful models, motivated by bootstrap rather than fundamentalist thinking. Any single model necessarily must contain "arbitrary" parameters, representing the limitations of that model, but the parameter of one bootstrap model may be explained by another. Each bootstrap model is <u>intended</u> to cover only a portion of the entire S matrix, but experience has shown that there can be regions of overlap.

Hopefully, the previously described partially successful models based on fundamentalist thinking all will be reformulated from the bootstrap point of view and will be supplemented by a unending series of additional models, each with its special capabilities and limitations. Wider and wider regions of the S matrix may gradually be covered, with greater and greater accuracy, by a combination of models whose <u>net</u> number of "arbitrary" parameters keeps decreasing. Although the entire S matrix never will be encompassed by any human effort, a sufficiently sustained trend eventually might convince the physics community that all hadronic phenomena indeed flow from self-consistency.

Even though obscured by the fundamentalists' embrace, the history of the Veneziano model is encouraging for bootstrappers. It is hard to imagine this model being invented by a fundamentalist; it resulted from years of effort to understand how Regge behavior can be compatible with particle-antiparticle continuation (crossing). Unitarity was sacrificed. allowing the arbitrariness of widths already emphasized, but this compromise was motivated by the observed smallness of widths, not by any belief that certain special parameters are intrinsically arbitrary. The bootstrapper expects that some model quite different from that of Veneziano will explain the observed magnitude of resonance widths.

Any individual model, even if motivated by bootstrap thinking, evidently can be co-opted by fundamentalists. Once a model has thus been embraced, however, its parameters assume a special status in the eyes of the fundamentalist, who thereby is inhibited from considering on an equal footing other models whose parameters are different. Conversely, a physicist who is able to view any number of different partially successful models without favoritism is automatically a bootstrapper. One can thus imagine that the development of an increasing number of models of comparable power, but differing in the range of phenomena to which they apply, gradually will transform more and more hadron physicists into bootstrappers.

The unfriendly question raised most often by sharp-witted fundamentalists is how self-consistency can possibly be expected to generate "internal quantum numbers" like hypercharge and baryon number. It is conceded that mass ratios and coupling constants might all be bootstrappable, but how can you bootstrap a symmetry? A conceivable response is that symmetries (or the associated quantum numbers) are related to particle multiplicities, and the nonlinear unitarity condition responds to the number of different particles. Models that incorporate unitarity in some serious fashion (not through a formal but meaningless infinite series) thus have a chance of shedding light on the internal-quantum-number puzzle. If some future bootstrap-motivated model succeeds in "explaining" baryon number and hypercharge, the most skeptical of fundamentalists ought to be impressed.

A politically loaded question concerns the relative importance of experiments at extremely high energies if the hadron bootstrap hypothesis turns out to be valid. There remain puzzles concerning asymptotic behavior that clearly will benefit from much higher accelerator energies than currently available, but it should not be assumed that all important experiments in the region of a few GeV have already been performed. For example, bootstrap models suggest poles of all conceivable quantum numbers, so high-resolution spectroscopy may reveal a far richer moderate-energy spectrum than currently supposed. The role of branch points, furthermore, is a fertile field for high-precision experiments; in a bootstrapped S matrix all singularities are of comparable intrinsic significance. By the same token, all energies are of comparable interest--from the highest to the lowest.

THE DISTANT FUTURE

Once the bootstrap idea is raised, the mind immediately leaps beyond the hadron arena. A complete bootstrap has enormous esthetic appeal, and one inevitably hears the question, "Why stop with the hadrons?"

On a very long time scale the self-consistent approach, if useful for hadrons, will surely be extended. The difficulty at present is one of language. Hadron physics can be discussed in the language of the analytic S matrix because there exist no zero-mass hadrons to generate interactions of infinite range in space-time. Existing S-matrix language is inapplicable to phenomena involving zero-mass particles; we shall require a more general framework, and as suggested in our introduction, it is plausible that to understand zero-mass phenomena through self-consistency may require bootstrapping space-time itself.

Such a profound step as understanding the origin of space-time seems unlikely to occur within the lifetime of the present generation of physicists. But if we succeed in laying the foundation for such a step, to be taken by a future generation, 20th-century particle physicists will justifiably assess the outcome of their struggle as a triumph.

FOOTNOTES AND REFERENCES

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