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String Theory: The Early Years

John H. Schwarz[1]
California Institute of Technology
Pasadena, CA 91125, USA

Abstract

Lenny Susskind has made many important contributions to theoretical physics during the past 35 years.

In this talk I will discuss the early history of string theory (1968-72) emphasizing Susskind's contributions.

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1 S-Matrix Theory, Duality, and the Bootstrap

In the late 1960s there were two parallel trends in particle physics. On the one hand, many hadron resonances were discovered, making it quite clear that hadrons are not elementary particles. In fact, they were found, to good approximation, to lie on linear parallel Regge trajectories, which supported the notion that they are composite. Moreover, high energy scattering data displayed Regge asymptotic behavior that could be explained by the extrapolation of the same Regge trajectories, as well as one with vacuum quantum numbers called the *Pomeron*. This set of developments was the focus of the S-Matrix Theory community of theorists. The intellectual leader of this community was Geoffrey Chew at UC Berkeley. One popular idea espoused by Chew and followers was "nuclear democracy" – that all hadrons can be regarded as being equally fundamental. A more specific idea was the "bootstrap", that the forces arising from hadron exchanges are responsible for binding the hadrons, as composites of one another, in a more or less unique self-consistent manner.

The second major trend in the late 1960s grew out of the famous SLAC experiments on deep inelastic electron scattering. These gave clear evidence for point-like constituents (quarks and gluons) inside the proton. This led to Feynman's "parton" model, which was also an active area of research in those days. I would submit that Susskind was philosophically more in tune with the parton world view than the S matrix one, though he clearly had a foot in each camp. My Berkeley training put me solidly in the S-matrix camp.

In the early 1970s, it became clear that QCD is the correct theory of strong interactions. It can be used for explicit computations in large momentum regimes where perturbation theory can be used, thanks to asymptotic freedom. Modern phenomenological studies in such regimes are directly descended from the older parton models. In other regimes, such as diffraction scattering, where perturbation theory is not applicable, S-matrix ideas are still used. So both major trends from the late 1960s have their descendents 30 years later.

String theory, which is the subject I want to focus on here, grew out of the S-Matrix approach to hadronic physics. The bootstrap idea got fleshed out in the late 1960s with the notion of a duality relating s-channel and t-channel processes that went by the name of "finite energy sum rules" [1] - [7]. Another influential development was the introduction of "duality diagrams", which keep track of how quark quantum numbers flow in various processes [8, 9]. Susskind contributed papers on this topic [10, 11]. Later, duality diagrams would be reinterpreted as string world-sheets, with the quark lines defining boundaries. A related development that aroused considerable interest was the observation that the bootstrap idea requires a density of states that increases exponentially with mass, and that this implies the existence of a critical temperature, called the Hagedorn temperature [12] - [15]. It was

generally supposed that this it is an ultimate temperature, though a phase transition was clearly another possibility.

2 The Dual Resonance Model

The duality program got a real shot in the arm in 1968 when Veneziano found a specific mathematical function that explicitly exhibits the features that people had been discussing in the abstract [16]. The function, an Euler beta function, was proposed to give a good phenomenological description of the reaction $\pi + \omega \to \pi + \pi$ in the narrow resonance approximation. This was known to be a good approximation, because near linearity of Regge trajectories implies that the poles should be close to the real axis. A little later Lovelace and Shapiro proposed a similar formula to describe the reaction $\pi + \pi \to \pi + \pi$ [17, 18]. Chan and Paton explained how to incorporate "isospin" quantum numbers in accord with the Harari–Rosner rules [19]. Also, within a matter of months Virasoro found an alternative formula with many of the same duality and Regge properties that required full s-t-u symmetry [20]. Later it would be understood that whereas Veneziano's formula describes scattering of open-string ground states, Virasoro's describes scattering of closed-string ground states.

In 1969 several groups independently discovered N-particle generalizations of the Veneziano four-particle amplitude [21] - [25]. The N-point generalization of Virasoro's four-point amplitude was constructed by Shapiro [26]. In short order Fubini and Veneziano, and also Bardakci and Mandelstam, showed that the Veneziano N-particle amplitudes could be consistently factorized in terms of a spectrum of single-particle states described by an infinite collection of harmonic oscillators [27] - [30]. This was a striking development, because it suggested that these formulas could be viewed as more than just approximate phenomenological descriptions of hadronic scattering. Rather, they could be regarded as the tree approximation to a full-fledged quantum theory. I don't think that anyone had anticipated such a possibility one year earlier. It certainly came as a surprise to me.

One problem that was immediately apparent was that since the oscillators transform as Lorentz vectors, the time components would give rise to negative-norm ghost states. Everyone knew that such states would violate unitarity and causality. Virasoro came to the rescue by identifying an infinite set of subsidiary conditions, which plausibly could eliminate the negative-norm states from the spectrum [31, 32]. These subsidiary conditions are defined by a set of operators, which form the famous Virasoro algebra [33]. The central term in the algebra was discovered by Joe Weis (unpublished). One price for eliminating ghosts in the way suggested by Virasoro was that the leading open-string Regge trajectory had to have unit intercept, and hence, in addition to a massless vector, it contributes a tachyonic ground

state to the spectrum [34].

3 The String Idea

Once it was clear that we were dealing with a system with a rich spectrum of internal excitations, and not just a bunch of phenomenological formulas, it was natural to ask for a physical interpretation. The history of who did what and when is a little tricky to sort out. As best I can tell, the right answer – a one-dimensional extended object (or "string") – was discovered independently by three people: Nambu, Susskind, and Nielsen. Nambu's contribution to the 1969 conference held at Wayne State University apparently was first, but the conference was rather obscure [35], and the paper was not widely circulated. His subsequent paper, submitted to a symposium in Copenhagen, proposed that the string action is the area of the world-sheet in analogy with the proper length of the world-line of a point particle [36]. These difficult to find papers have been reprinted in [37].

The string idea also appears quite clearly in Susskind papers, which were published in a refereed journal [38, 39, 40]. Nielsen's first paper on the subject was submitted to a 1970 conference in Kiev, though it was not published in the proceedings [41]. However, shortly thereafter, he and Fairlie described their approach in a refereed journal [42]. The Nielsen papers emphasize an analog electrostatic model in which one solves Laplace's equation on a disk with sources on the boundary. This is just the string wave equation on a Euclideanized world sheet. The electrostatic analogy was also discussed by Shapiro for the Virasoro–Shapiro model taking the domain to be a sphere rather than a disk and with the sources attached to the interior of the surface [26]. We recognize this to be the proper description of tree-level closed-string amplitudes.

A somewhat different approach treated the string world-sheet as some kind of sum or limit of complicated planar Feynman diagrams, sometimes referred to as fishnet diagrams. This approach, along with various related parton ideas, was pursued by Sakita and Virasoro [43] as well as by Susskind and Nielsen [44] - [50]. Note that these works are several years prior to 't Hooft's famous paper on large-N gauge theory [51]. They were not very specific, however, about which field theory should be used to form the fishnet diagrams or what limit was required to make contact with a string world sheet.

Though there was some progress in the intervening years [52, 53], the string interpretation of the dual resonance model was not very influential in the development of the subject until the appearance of the 1973 paper by Goddard, Goldstone, Rebbi, and Thorn [54]. It explained in detail how the string action could be quantized in light-cone gauge. Subsequently Mandelstam extended this approach to the interacting theory [55].

4 Loop Amplitudes

From the factorization of N-particle amplitudes one had learned the tree approximation spectrum and couplings. With this information in hand, it became possible to construct one-loop amplitudes. The first such attempt was made by Kikkawa, Sakita, and Virasoro [56]. They did not have enough information in hand to do it completely right, but they pioneered many of the key ideas and pointed the way for their successors [57] - [66].

Those who worked on this problem included a group at Princeton consisting of David Gross, André Neveu, Joël Scherk, and myself. Another group consisted of Lenny Susskind and various collaborators. Neveu and Scherk studied the divergence of the one-loop planar amplitude. They realized that by performing a Jacobi transformation of the theta functions in the integrand they could isolate the divergent piece and propose a fairly natural counterterm [63]. Essentially the same thing was done independently by Susskind and Frye [64]. The modern interpretation of these results is that viewed in a dual channel there is a closed string going into the vacuum. The divergence can be attributed to the tachyon in that channel. Its contribution is the piece they subtracted. This also explains why in a model without tachyons such divergences would not occur. The cancellation of the milder divergences due to dilaton tadpoles also became an important consideration in later years.

One of the important things discovered by the Princeton group [59], which was discovered independently by Frye and Susskind at about the same time [65], was that the nonplanar loop amplitude gives new and unexpected singularities. In both of these works the dimension of spacetime was assumed to be four, and the Virasoro subsidiary constraints were not implemented on the internal states circulating in the loop. As a result the singularities were found to be unitarity-violating branch points.

Lovelace observed that if one allows the spacetime dimension to be 26 and supposes that the subsidiary conditions imply that only transverse oscillators contribute, then instead of branch points the singularities would be poles [67]. As we now know, these are are the closed-string poles in the nonplanar open-string loop. This calculation showed that unitarity requires that one choose the critical dimension and the intercept value for which the Virasoro conditions are satisfied. In those days these states were referred to as Pomeron-states rather than closed string states, since they necessarily carried vacuum quantum numbers. It was supposed that the unphysical Regge intercept value of two – implying the existence of a massless spin two particle as well as a tachyon – would somehow be lowered to the desired value of one in a more realistic model.

Shapiro carried out the first closed-string loop calculation [69]. Specifically, he computed the one-loop (torus) amplitude.

5 Conclusion

The younger generation of theoretical physicists is aware of the wide range of important contributions that Lenny Susskind has made to our field in recent years. What they may be less aware of is his important role in the early history of string theory. I hope this presentation will help to publicize that work.

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