Gravity from strings: personal reminiscence on early developments

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Abstract

I discuss the early developments of string theory with respect to its connection with gauge theory and general relativity from my own perspective. The period covered is mainly from 1969 to 1974, during which I became involved in research on dual string models as a graduate student. My thinking towards the recognition of string theory as an extended quantum theory of gravity is described. Some retrospective remarks on my later works related to this subject are also given.

1. Prologue: an encounter with the dual string model

I entered the graduate school of Hokkaido University, Sapporo, in April, 1969. My advisor, Akira Kanazawa who was an expert in dispersion-theoretic approach to strong interactions, proposed having a seminar on Regge pole theory regularly every week together with a few other students. Comparing with various marvelous theories which I had learnt during undergraduate studies, however, the Regge pole theory was somewhat disappointing for me. I felt that it was too formal and phenomenological in its nature without much physical content, except for interesting mathematical physics related to the notion of complex angular momentum. Looking for some more favorable topics, I became interested in studying the quantum field theory of composite particles, which, I thought, might be useful to explain the Regge-pole behavior from the dynamics of fundamental particles. I read many papers related to this problem such as those on compositeness criteria, on the definition of asymptotic field for a composite particle, and especially on the Bethe-Salpeter equation. Although I felt that this subject was not yet what I really would want to pursue, I learnt much about quantum field theory by studying these papers.

*Invited contribution to the book "The Birth of String Theory".
While still seeking subjects for my research, some senior students told me that there was actually a spectacular new development triggered off by a proposal made a year ago by Veneziano [Ven68]. After reading the paper of Veneziano and some others which extended the Veneziano amplitude to various directions, I gradually became convinced that this had to be the subject I should choose. In particular, when I was exposed to a short but remarkable preprint by Susskind [Sus69] giving a physical interpretation of the Veneziano formula in terms of vibrating strings (or ‘rubber band’ in Susskind’s terminology), I was struck by the simplicity of the idea. My interest on dual models was further strengthened by reading the paper by Nambu [Nam70], containing similar discussions. In particular, I was intrigued by the concept of ‘master field’ (in today’s language, string field), which had been emphasized by Nambu. A little later I also came to be fascinated by the very attractive world-sheet picture of Fairlie and Nielsen [FN70].

In spite of encountering such stunning ideas, my interests in dual models remained mostly within the realm of more formal aspects of dual models during my years in graduate school, as was perhaps common among many other young students who became interested in this field in the same period. By the beginning of the autumn of 1969, I started to study various available preprints, which were very rapidly growing. They included works on factorization, operator formalism, and unitarization program.

One of the papers which I was most interested in during this period was the one by Fubini and Veneziano [FV70]. They introduced an extremely elegant formulation of factorization and duality for general \( n \)-point amplitudes in terms of a vertex operator \( \exp i k_{\mu}Q^\mu(z) \): for tachon as the ground state of the dual string. I thought that this formalism not only was suggestive from the physical viewpoint of vibrating strings, but also was quite important in making manifest the key symmetry structure, Möbius symmetry or \( \text{SL}(2, \mathbb{R}) \) invariance, underlying the basic duality property of the amplitudes as had been exhibited by the Koba-Nielsen representation [KN69]. On the other hand, from the viewpoint of the unitarization program which had been initiated in a remarkable work by Kikkawa, Sakita and Virasoro (KSV) [KSV69], it was a crucial step to construct amplitudes or vertices with the most general external lines corresponding to general excited states of strings. Attempts towards such ‘Reggeon’ vertices were started by Sciuto [Sci69]. During the years from 1969 to 1971, there appeared a large number of papers discussing this problem.

In the Japanese system of graduate school, we usually have to present a thesis in order to finish the first two years, ‘master course’, of graduate study before entering the next stage, ‘doctor course’, of three years. As the subject of my master thesis, I decided to try, by utilizing the symmetry structure uncovered by the Fubini-Veneziano formalism, to establish a formalism of the Reggeon vertices such that the duality symmetry and factorization property were exhibited as manifestly as possible. I realized that a similar direction had been pursued in some papers that I became aware of, such as those by
Lovelace [Lov70] and Olive [Oli71]. I was able to achieve such a goal by adopting a general method proposed earlier by Shapiro [Sha70b] for factorizing the generalized Veneziano amplitudes. I applied this method to a multiple factorization of the Fubini-Veneziano's operatorial form of the $n$-point amplitudes. The resulting general $n$-point Reggeon vertex enjoyed desired symmetry properties with respect to gauge, twisting, factorization and duality transformations. It also contained the previous results due to Lovelace and Olive as special cases. This small work [Yon71] became my first full paper. Through this work, I acquired a certain personal confidence in engaging myself further in this research field, although I was working alone in a way almost completely isolated from the centers of dual model research. After many years, I met C. Montonen at the Strings 2002 conference in Cambridge. According to him, my work had some influence on his work [CM72] with E. Corrigan in which they discussed a group theoretical formulation of the Reggeon vertices. In fact, I remember that my preprint had been cited in their paper. It was an unexpected surprise for me to have an enjoyable conversation related to such old works more than three decades later.

2. Connection of dual models to field theories

From these early days of my studies on dual models, there had been one basic question which was increasingly occupying my mind. That was on the relationship between dual models and ordinary field theory. In characterizing the Veneziano amplitude, it had been emphasized that the amplitude could be expanded into a sum over an infinite set of either $s$-channel poles or $t$-channel poles, but not of both. Adding both would amount to double-counting. This is of course the statement of channel duality, which had motivated the original proposal of the Veneziano amplitude. However, the unitarization program started by the KSV paper seemed to be an extension of the usual Feynman-graph expansion in ordinary field theory, in which we have to sum both $s$- and $t$-channel diagrams. One of my questions was whether it would in principle be possible to find a field theory from which such an extended dual Feynman-graph expansion would be derived, perhaps by introducing some appropriate interactions for Nambu’s master field.

Another related question was on the interpretation of massless spinning excitations. The existence of such states in dual string models is an inevitable consequence of conformal symmetry associated with the Virasoro operators. In contrast to this, the existence of massless spinning fields in the framework of ordinary field theory is related to local gauge symmetries. During my master-course years, I became strongly interested in the local gauge principle, through reading the original papers by Yang and Mills and by Utiyama, in addition to those related to composite particles as mentioned above. Because my main interest had been in strong interactions, I was naturally seeking papers aiming applications of the local gauge principle to strong interactions. In regard to later works following the
above classical works, the paper most intriguing to me was the one by J. J. Sakurai [Sak60]. I was deeply impressed by a strong persuasive power of this work. I thought that if the local gauge symmetry could be such a fundamental principle for strong interaction, it should also play some role in dual models, and then the existence of massless spinning states in the latter had to be a clue.

A gauge theory interpretation of massless spinning states

After submitting my master thesis in the beginning of 1971, I decided to pursue the second question above as my next theme. I attempted first to interpret the interaction vertices of the massless vector states of open strings in terms of a local gauge transformation for string wave functions. I soon realized that all those vertices in the Veneziano, Neveu-Schwarz [NS71] and Ramond [Ram71] models were precisely obtained by a minimal substitution

$$p^\mu(\sigma) \rightarrow p^\mu(\sigma) - gA^\mu(x(0))\delta(\sigma)$$

with $\Box A^\mu = 0$ corresponding to a particular class of local-gauge transformations on the master field $|\Psi\rangle$, such as

$$|\Psi\rangle \rightarrow e^{ig\lambda(x^\mu(0))}|\Psi\rangle \quad (2.1)$$

under an on-shell condition $\Box \lambda(x) = 0$ for the gauge function $\lambda(x^\mu)$, where $x^\mu(0)$ is the string coordinate at an end point $\sigma = 0$ of open strings. Namely, I showed that the vertices obtained from the Virasoro or super-Virasoro operators in this way coincided with those obtained by factorizing the pole residues at corresponding massless poles. I interpreted this simple fact as clear evidence for the fact that these massless vector states themselves should be regarded as gauge bosons and that the world-sheet conformal symmetry was the mechanism which made the local gauge symmetry intrinsic to dual strings. In modern language, this formulation is of course equivalent to the vertex operator introduced as a deformation of the world-sheet action by background gauge field at the boundary of open-string world sheets.

When I was pursuing this idea, I became aware of some prior works which were trying to apply local gauge principles to dual models, such as those by Kikkawa-Sato [KS70] and by Manassah-Matsuda [MM71]. However, the standpoint common to these two works was entirely different from my viewpoint, in the sense that they were aiming toward constructing off-shell currents which would make possible the coupling of electromagnetic and weak interactions to dual strings. Hence, in their works, the gauge bosons coupled to the Veneziano amplitudes were nothing to do with the massless spinning states of dual strings themselves.

I wrote up a paper on my result, emphasizing that the conformally invariant dual models of open strings should be regarded as embodying local gauge principle intrinsically, rather than interpreting the latter as some external structure to be artificially adjoined to the dual models. I submitted it to Nuovo Cim. Unfortunately this manuscript was rejected for the reason, as far as I remember, that the vertices discussed in it were not new. This rejection disappointed me. However, to my knowledge at that time, no one had expressed the same viewpoint as mine on the meaning of local gauge
principle in string theory.

A few months after this experience, I received a letter commenting on my preprint on the gauge principle in dual models from M. Minami, who was at the Research Institute of Mathematical Sciences (RIMS) in Kyoto and was actively engaged in dual models. To his letter, there was an attached copy of a preprint by Neveu-Scherk \[NS72\] on the application of Scherk’s work \[Sch71\] on the zero-slope limit to the dual pion model of Neveu and Schwarz, making a connection to gauge theory. Minami also mentioned some works by Nakanishi \[Nak71\] on a crossing-symmetric decomposition of the integral representation of the Veneziano-type amplitudes in such a way that each decomposed piece corresponds to a usual Feynman graph only with pole singularities in a single definite set of channels. All these works which I had not been aware of until that time were a big surprise to me.

As for the rejected manuscript which I was almost trying to forget, I decided to rewrite it in a more compact form. I sent it to Prog. Theory. Phys. \[Yon72a\] in which I added an acknowledgement to Minami.

Minami’s letter encouraged me to pursue my interpretation further. I immediately hit upon an idea of extending it to the case of closed strings, namely to the Virasoro-Shapiro amplitudes \[Vir69\][Sha70a]. However, making a connection to gravity seemed to be a rather bizarre thing to do, since at that time everyone thought that the dual string model was aiming at the construction of a definitive theory for hadrons and their strong interactions. Actually, during my undergraduate years, I had been quite serious about Einstein’s general relativity theory and had studied even some of the original papers. In fact, Einstein had been basic impetus to me, since I had started out on trying to comprehend his book ‘The meaning of relativity’ during my high school day. However, after entering the graduate school and being influenced by the atmosphere of the particle physics community, I became quite strongly prejudiced against general relativity, regarding it as a sort of a relic of the past. In the case of the vector gauge principle, I was able to free myself from similar prejudice by reading the Sakurai paper and others. I hoped that the connection to gauge theory would be useful in trying to give masses to the unwanted massless states, in the way \(\rho\) mesons were related to the gauge principle as Sakurai had advocated. But in the case of gravity, to my knowledge at that time, there had been no such attempt. It took another year for me to come back to this idea again.

**Extension of the Nakanishi decomposition and a desperate attempt toward string field theory**

Studying Nakanishi’s beautiful papers on the decomposition of the integral representation for the \(n\)-point dual amplitudes, I gradually returned to my first question concerning the relationship between dual models and field theory. From the viewpoint of my question whether the dual amplitudes could be derived from some field theory, I thought that Nakanishi’s way of decomposing the amplitudes had to be one of the necessary steps. Then, I realized that what I had done in my master thesis would fit quite nicely in order
to reformulate Nakanishi’s result in such a way that the rule of decomposition is expressed as a generalized Feynman-like rule. That would make it possible to extend the decomposition to arbitrary loop diagrams. It had been well known that a naive application of the operator formalism, in the case of non-planar diagrams, led to a divergence difficulty [KT70], known as the ‘periodicity’ problem, of integrating over one and the same contribution infinitely many times. I was able to confirm that the rules I had derived on the basis of my previous Reggeon-vertex paper indeed resolved this difficulty as expected, because my new Feynman-like rule automatically gave a definite prescription for the integration region for arbitrary diagrams. Also this rule involving only a generalized 3-point vertex naturally reduced to that of the $\phi^3$ theory in the zero-slope limit discussed by Scherk.

I was certainly excited by this result, since this strongly suggested that the rule I had derived might correspond precisely to the Feynman rule of a desired string field theory. When I was finishing the paper about this result in May 1972, I was staying about a month at the Yukawa Institute in Kyoto, having discussions on this and related problems with Nakanishi at RIMS. As soon as I completed the paper [Yon72b] on this result in Kyoto, I turned to attempt constructing such a formalism. Seeking some hint for a new field theory underlying the dual string models, I studied some old works on infinite-component field theories and especially non-local field theories, including papers by Yukawa [KY68]. Unfortunately, however, I did not get really useful insight, since most of those works had been essentially restricted to free theories. In addition to this, the rule I had presented was using a very cumbersome language, which had inherited from Nakanishi’s original method and my own formulation of the general Reggeon vertex, and hence did not allow simple interpretation in terms of more intuitive world-sheet picture. What I was trying to do is equivalent to obtaining a covariant triangulation of the moduli space of Riemann surfaces with boundaries and punctures such that it corresponds to a second-quantized field theory of interacting open strings. More than a decade later in 1985, Witten achieved this goal [Wit86] in his proposal of a covariant open string field theory, on the basis of the BRST operator formalism.

A version of fully interacting string field theories first appeared on the scene in 1974, when Kaku and Kikkawa published their work [KK74]. Their formulation was based on Mandelstam’s light-cone representation [Man73] of the dual amplitudes which had appeared about a year later after my failed attempt towards string field theory. The light-cone string field theory provided another possible, albeit non-covariant, triangulation of the moduli space of Riemann surfaces.

Connection of dual models to general relativity

By the failure of my desperate attempt toward string field theory, I was quite exhausted. To recover from a depressed mood which I fell into, I had to spend almost half a year from the summer of 1972, wandering about various other topics. From about this period onward, many people were departing from the dual string models. But I had
some feeling that the dual models themselves contained something more to be uncovered, despite their immediate inapplicability to the physics of hadronic interactions. I was also influenced by a rapid resurgence of gauge field theories, which had been initiated by 't Hooft's famous work on the renormalizability of non-abelian gauge field theories. I was now thinking seriously about my previous idea on a possible connection between dual string models in the case of closed strings and general relativity. In studying the progress in gauge field theories, I was gradually freeing myself from the prejudice on general relativity. I thought that as the Yang-Mills theory had turned out to be useful in this way, general relativity might also become important for particle physics someday in some unexpected way. I also felt that it was good for me to return, now in the last stage of my graduate study, to general relativity which after all had been the prime impetus toward theoretical physics for me.

My thinking was something like this: One of the useful viewpoints on dual string models which had been made clear by Scherk's work was that the slope parameter $\alpha'\!$ should be treated as a fundamental constant as the Planck constant $\hbar$ had been for quantum theory. It would be very exciting if we had some kind of concrete correspondence principle between dual string models and general relativity, in an analogous way as in the case of the relation between, say, the canonical commutation relation in quantum mechanics and the Poisson bracket in classical mechanics. In any case, I had first to study a nontrivial example of the zero-slope limit for the Virasoro-Shapiro amplitudes. I decided to compute a 4-point amplitude involving two massive scalars and two gravitons, since the coupling of graviton to scalars was certainly the simplest case, as had been treated in most of old literatures which I had come across in this subject. All such papers of course only discussed the case of 4 dimensions, and I was not attempting to generalize them to critical dimensions, since for discussing only the properties of massless modes of strings without loop corrections we could restrict ourselves to lower dimensions. Consequently, the Newton constant was identified to be proportional to $g^2\alpha'$ with $g$ being the 3-point coupling constant of closed strings. Staying in 4 dimensions made possible for me to assign an arbitrary (real) mass to the scalar (tachyonic in critical dimensions) ground state treated as a matter field coupled with gravity, using additional components of momentum along the extra dimensions. In the early summer of 1973, I decided to publish the result [Yon73] of such a computation first in a letter form.

In parallel to this computation, I was pursuing a question on how to establish the correspondence to all orders with respect to graviton interactions in the tree approximation, or in other words to the tree amplitudes with arbitrary number ($= n$) of gravitons and with a fixed number ($=2$) of massive scalars. Since general relativity is a non-polynomial field theory, I needed a certain general theorem for the purpose of establishing the connection in a recursive way on the basis of my explicit computation of the (2+2)-point amplitude. I found a paper which was quite suitable for this aim. That was the one by
W. Wyss [Wys65] who had given a very clear argument on how the non-polynomial Einstein Lagrangian is obtained, starting from the lowest order coupling between a massive scalar field and a massless spin 2 field.

The second and more ambitious question was, as alluded to already, to find an appropriate correspondence principle which would lead from general relativity to the dual strings in a more or less unique way. An ideal thing which I was dreaming of would be to find something analogous to what had been happening in the discovery of quantum mechanics. I was also recalling P. Ramond’s argument [Ram71] in his proposal of the dual fermion model as a generalization of the Dirac equation. Unfortunately, however, I was not able to find such a correspondence principle in any satisfactory form. I could give only a modest discussion, which was related to a generalization of the equivalence principle, about the generating functional for the S-matrix for \((n + 2)\)-point scatterings:

\[ \text{The S-matrix on the string side can be obtained from that of field theory by making a simple reinterpretation for the space-time energy momentum tensor of a massive scalar field.} \]

The third point I was thinking about was a question whether there could exist an extension of the Nakanishi decomposition to the general Virasoro-Shapiro amplitudes. That would make it possible to connect both sides in a more direct way by comparing the Feynman rules on both sides. I failed to arrive at really useful conclusion on this question, except for an expectation that in this case the decomposition would require most probably an infinite number of higher-point vertices as we go to the higher-point graviton amplitudes.

Although these failures somewhat disappointed me, I decided to write a full paper on the connection between the dual closed strings and general relativity. The title of the paper that I chose was ‘Connection of Dual Models to Electrodynamics and Gravidynamics’, which was sent to Prog. Theor. Phys. [Yon74a] in the early autumn of 1973. The reason why I put also the word ‘Electrodynamics’ was that I included in the paper an argument for the similar case of the open-string scattering of \(n\) massless vectors and 2 massive scalars. That was intended for the purpose of emphasizing the similarity and, simultaneously, the contrast of the arguments between electrodynamics and gravidynamics, especially with respect to the second question above.

I remember that, while writing this paper, my mind was in a somewhat perplexed state. One of the reasons was that I was not completely sure about my standpoint in interpreting the connection of the dual models to gravity. After my first seminar on my paper in our high-energy laboratory, a senior student (S. Araki) privately asked me

\[ ^1 \text{Many years later, I have presented some considerations which I had made at that time along this direction in a review talk [Yon86] on string field theory in a workshop held at Komaba in 1986. In the late 80s, essentially the same problem was discussed by several groups in attempting to extend Witten’s covariant open string field theory to closed strings. A systematic discussion along this line was given by Zwiebach [Zwi92].} \]
something like this‡. “So, are you claiming that the dual model is more fundamental than the Einstein theory, replacing the latter by the dual model?” I was slightly upset by this pressing question. As far as I remember, my answer was “Well, as I have said, I could not find any definite principle, relating the dual model to general relativity. If I could have provided such a deeper explanation, I might have a right of claiming that. All what I can say is simply a fact that we can extract general relativity from the dual model in this way.” Rather than thinking toward the application of my results to the real world, I was mostly occupied by a desire to understand a deeper reason for why the theory of relativistic strings happens to automatically encompass general relativity, the latter being based on such deep principles as the equivalence principle and general covariance. I confess that I did not have sufficient courage to make such a bold statement, since I had been too strongly worried by lack of fundamental principles for explaining the emergence of gravity from strings.

Furthermore, my mind was also entangled with another competing viewpoint on the relationship between the dual string models and field theory. Already in 1970, there had been suggestive discussions on planar ‘fishnet’ diagrams by Sakita-Virasoro [SV70] and Nielson-Olesen [NO70]. Their elegant observation had also been quite attractive to me as another possible attitude towards an understanding of the relation between dual models and local field theories. Moreover, in 1973, Nielsen and Olesen had published an interesting pair of papers [NO73a] [NO73b] in which they discussed the possibility of embedding relativistic strings in local field theories, either as a gauge theory with a non-linear field equation corresponding to the lagrangian $-\sqrt{F^2}/2\alpha'$ or as a vortex solution to a gauge-Higgs system, respectively. I became aware of these preprints just about the time when I was working on the connection of dual models to gravity on the basis of the zero-slope limit. These works were suggesting that the dual string might well be a consequence from non-linear gauge-field theories, resulting from their nontrivial dynamics. This is a view which is completely opposite to the derivation of field theories from the dual models in the zero-slope limit. I was asking myself, “Does this then imply that general relativity can be contained in gauge theory?”.

I have not been able to resolve this puzzle for many years. When I was invited in 1975 from the journal ‘Butsuri’, a periodical (in Japanese) of the Physical Society of Japan, to write a brief report [Yon76a] on the recent development of dual models with respect to the relationship between the dual models and field theory, I began the article as: “Since the dual resonance model has started out without any explicit connection to field theory, it has been one of the basic questions how the relationship between the dual model and field theory should be understood. There are two possible answers. One is that the dual

‡ I cannot confirm this to Araki, since unfortunately he passed away in 1994.

§ These works were precursor to the seminal work [THo74] of ’t Hooft on planar diagrams in the large $N$ limit.
string is something which is beyond the framework of ordinary local field theory, and
the latter should be interpreted as a particular limiting case of the dual string model.
Another possibility would be that although the dual model cannot be understood using
the traditional perturbative methods of field theory, they may be properly derived from
field theory by means of some non-perturbative treatments of its complicated non-linear
dynamics. In the present report, I will discuss the recent developments from the first
viewpoint, relegating the second to other opportunities."

In the next year, several months after the submission of my paper, I received a preprint
by Scherk and Schwarz [SS74a] (see also [SS74b]) in which they had studied the zero-slope
limit of closed strings. In contrast to my approach of studying the coupling of gravitons
to an artificial massive scalar state mainly for a methodological reason, they treated the
amplitudes with only massless states. In 1975, furthermore, they made a bold proposal
[SS75] that the dual string models should be interpreted as a unified theory of quarks
and gluons. I was quite impressed by their works, especially by their clear attitude with
respect to the interpretation of the connection of the dual models to gravity.

At any rate, there were several reactions to my work. In the beginning of 1974, I
was invited to give a talk in a workshop organized by the GRG (general relativity and
gravitation) group in Japan, and I met some of the leading Japanese physicists working in
this field, including R. Utiyama. In the early summer of the same year, I received a letter
from Y. Hara who was then staying in Europe, telling me that the connection of dual
models to gravity was discussed by D. Olive in an international conference in London.
Hara encouraged me to go to the United states for my postdoctoral studies. Subsequently,
I received a letter from B. Sakita asking me whether I was interested in joining his group
at the City College, New York. I also met K. Kikkawa who came back to Japan from
there. Very stimulating conversations with him were most encouraging. Since I was
actually about to be offered a faculty position at Hokkaido University, I joined Sakita’s
group, from 1976 to 1978 during which I met A. Jevicki and S. Wadia, after fulfilling my
teaching duty at Hokkaido for one and a half years. In 1980, I moved to the Komaba
campus of the University of Tokyo.

In these periods, my interest in dual strings was almost completely diminishing, be-
cause I was sparked by the fascinating development of gauge theories, especially by various
new discoveries in non-perturbative aspects of gauge theories, such as magnetic monopoles,
instantons and lattice gauge theories. I became interested more and more in the dynamics
of non-Abelian gauge theories, especially in the question of quark confinement, on which
I was mainly working for a few years from the late 70s to the early 80s, though my papers
at that time included actually an attempt [Yon81] to derive a version of string field theory
as an effective theory of hadronic strings directly from lattice Yang-Mills theory: In fact,
I considered a generalized gauge transformation, which was not so dissimilar to (2.1), of
string field associated with Wilson loops to apply it for a reformulation of topological
structure of the algebra of Wilson and ‘t Hooft loops. Then from the late summer in 1983, I stayed at CERN for one year. During my stay at CERN, M. Green made a visit and gave a seminar. Green’s talk was quite stimulating to me, especially through his enthusiasm for string theory. As far as I remember, he gave a review of his works with Schwarz, but not yet on anomaly cancellation. From about this time, I became gradually inclined again to string theory, and the impact of their epoch-making work \[GM84\] on the anomaly cancellation brought me back to this field in the mid 80s. In fact, the works which I published during my stay at CERN were on the Liouville field theory and 2 dimensional gravity, close cousins of string theory.

Further related works

Before concluding this section, let me describe some of my further works, which are directly related to my earlier papers. After submitting the first full paper on gravity-string connection in 1973, I continued for sometime to think again about the possibility of establishing a Nakanishi-type decomposition for closed strings, since I thought that my discussion in connecting the closed string to general relativity should be improved to the level of a comparison between Feynman on both sides. In particular, I wanted to understand more clearly the mechanism of generating higher order interaction terms directly from the effect of massive excited states of the closed string. But convincing myself that this task was too difficult, I soon turned myself to more modest problems. First I went back to the connection of open strings to non-Abelian gauge theory, and decided to establish a detailed connection at the level of Feynman rules \[Yon74b\] on the basis of my previous work on the general Reggeon vertex and the Nakanishi decomposition.

Then, after a mathematical work \[Yon75a\] on an extension of the Fubini-Veneziano operator formalism using superfields which naturally arose by rewriting the Fairlie-Martin representation for the Neveu-Schwarz model, I also studied the coupling of graviton and other massless closed-string states to fermionic open strings. That was an extension of the formalism which I had developed earlier in the case of massless vectors. I showed \[Yon75b\], \[Yon76c\] that the vertex operators for these states were obtained by means of an extended local gauge principle similar to the ordinary tetrad formalism of local Lorentz gauge symmetry for the Dirac field, and discussed the associated geometric theory in the zero-slope limit. In particular in \[Yon76c\], I made a conjecture on how these properties would be realized in full-fledged string field theories. Ten years later, I showed the validity of this conjecture, when I discussed the symmetry structure associated with massless closed string states in the light-cone string field theory \[Yon85\], \[Yon87a\]. In fact, this result could have been obtained in the mid 70s if I had been devoting myself more seriously to the problem.

After sending the paper on this subject to Phys. Rev. Lett., I received a preliminary draft of the astonishing paper by Witten on a covariant open-string field theory \[Wit86\], in which he gave an impressive answer to the problem against which I had struggled in
vain more than 10 years ago. But I was pleased to see that he had cited my latest work
on the light-cone string field theory. The connection of Witten’s open string field theory
to the Nakanishi decomposition was noticed in a later paper by Giddings and Martinec
[GM86].

The above idea behind the paper [Yon85] is also related to my conjecture of a purely
cubic action which I have proposed [Yon87b] in the spring of 1986 at the ICOBAN ‘86
international workshop on Grand Unification, held at the city of Toyama located near
the site of the Kamiokande neutrino detector. In this workshop, there were also other
talks on string theory, including those by D. Gross and A. Strominger. Actually I had
discussed this conjecture earlier in a workshop in Kyoto in the beginning of the same year
or perhaps in the end of 1985. To my surprise, after only one or two months from the
Toyama workshop, I received preprints on possible realizations of my conjecture by Santa
Barbara group [HLTS86] and by Kyoto group [HIKK86], both mentioning my previous
talk in Toyama.

Finally, let me also mention that the expectation of a hidden correspondence principle,
which I had been seeking without success in the 70s for characterizing the departure of
string theory from general relativity, was basically the motivation for my later proposal
[Yon87c] [Yon89] in 1987 of an uncertainty relation for space-time. A decade later, this
idea turned out to be of some relevance for a qualitative understanding [LY97] of the
characteristic scales of D-brane dynamics. I have written several papers [Yon00] related
to this subject during years around the mid 1990s to the early 2000s.

3. Epilogue

Recalling what I was thinking during my student years from 1969 to 1974, I find somewhat
surprisingly how often my later works have been rooted in this period: I am still in quest
for better formulation of strings and D-branes along various lines which germinated, at
least partially, from these early ideas. I was working almost alone, but with occasional
kind help from other workers and, especially, in an environment of great progress which
was occuring in both string and gauge theories. I was fortunate in being able to start
working in such a dramatic period of particle physics.

After more than three decades passed, the developments in string theory in the recent
10 years through the conception of the gravity-gauge correspondence (or AdS/CFT cor-
respondence) are now throwing new light on my old perplexing question, the question of
whether ‘from general relativity to gauge theory’ or ‘from gauge theory to general relativ-
ity’. With respect to this puzzle, personally, a work [OY98] which I did with Y. Okawa in
1998 on a derivation of the gravitational 3-body force for D0 branes from the D0 gauge
theory (or M(atrix) theory [BFSS97]) was a small revelation to me. This work enabled
me to convince myself that general relativity may indeed be contained in the quantum
dynamics of gauge field theories, when interpreted as the theory for D branes.

In a sense, as if we are watching a revolving stage, the string theory came back to a scene, with which it had started in the early 70s, and is providing an entirely new perspective on gauge theory and even on hadron physics. However, we had to admit that we are still far from grasping fundamental principles behind string theory. Hopefully, we will see further dramatic turns in the next 30 years.

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