ON FACTS IN SUPERSTRING THEORY

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Abstract: Despite the lack of experimental confirmation and of unambiguous theoretical proof, superstring theory has long been considered by many the only consistent quantized theory of gravity and the unique viable framework for the unification of all fundamental forces of nature. In the first part of this essay I explore the type of reasoning used to support such statements. In order to illustrate the argument, in the second part I focus on one of the most acclaimed achievements of the theory: the AdS/CFT correspondence. Finally, I conclude by observing that what constitutes a result in superstring theory involves more than purely theoretical arguments. Specifically, the acceptance of facts in superstring theory is inextricably linked to the large group of people that make it possible, whether they are string practitioners or not.

1 The evolving scientific status of string theory results

Trying to overcome the impasse with what a massless particle with spin two meant for the dual model of strong nuclear interactions, in 1974 Joël Scherk and John Schwarz proposed a reinterpretation of this particle as the quantum carrier of gravitational force: “The possibility of describing particles other than hadrons (leptons, photons, gauge bosons, gravitons, etc.) by a dual model is explored. The Virasoro-Shapiro model is studied first, interpreting the massless spin-two state of the model as a graviton.” In their seminal paper Scherk and Schwarz showed that consistency of the dual model entailed a higher dimensional version of the Hilbert action. From this it then followed that the model included gravitational forces as described by Einstein’s equation. These were the primary motives driving the authors to propose that string theory quantized gravity: the spectrum showed a massless spin-2 particle, and, moreover, a ten-dimensional Einstein equation could be derived. In those days many theoretical physicists found these two results too weak to allege that a quantized theory of gravity had been achieved. This explains the cautious reception the theory received in its early years. Unexpectedly, however, this

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1 A detailed report on the sociological process here discussed is available at Spinning the Superweb: Essays on the history of superstring theory (www.spinningthesuperweb.blogspot.com). See section III and IV of the first essay “On Facts in Superstring Theory.” These last two sections are not included in this arXiv version!

2 J. Scherk and J. H. Schwarz, “Dual Models for Nonhadrons,” Nuclear Physics B 81 (1974): 118-144.
once feeble proposal has become widely established within theoretical physics, even though the mathematical support has remained almost unchanged for more than thirty years. Let us comment further on this.

In the last chapter of a classic string theory graduate textbook written in 1989, here is how the quantization of gravity is presented:

String theory is claimed to be a unifying framework for the description of all particles and their interactions, including gravity. However, up to now our exposition of the subject was rather formal and it is not at all transparent how it can be relevant for low energy phenomenology. The only hint we got so far was from looking at the spectrum. There especially the occurrence of a spin two tensor particle indicated that gravity might be contained in string theory.³

Note that this observation is relegated to the last part of the book, after some three hundred pages of mathematical details. No doubt this is a queer situation. Why leave the most important argument in favour of the theory, at least in popular accounts and undergraduate level materials, to the final pages of the textbook? The answer to this question is provided by the cautious words of the authors. Even more surprising is that the same argument has been used for decades. The only difference is that nowadays the quantization of gravity is not considered an “elusive task,” as many string theoreticians used to say, but rather an accomplished one. For example, in the midst of what string theorists consider the second major revolution of the field, Edward Witten wrote in Physics Today: “Moreover, these theories have (or this one theory has) the remarkable property of predicting gravity – that is, of requiring the existence of a massless spin-2 particle whose coupling at long distances are those of general relativity.”⁴ (Italics in the original.) And in an up to date textbook, aimed at undergraduate physics students, the author says: “The striking quantum emergence of gravitation in string theory has the full flavor of a prediction.”⁵ Understandably, declarations of this kind have given rise to hot discussions among supporters and detractors of the theory. The question is: what happened in those intervening years? Why are string theorists so optimistic now? Did they really find an unquestionable proof, experimental or theoretical, that their theory quantizes gravity?

In point of fact, to this day nobody has presented an entirely convincing proof of this. For some theoretical physicists, the presence of a massless spin-2 particle in its spectrum is not enough to a quantized theory of gravity. I is also argued that the low energy limit analysis of superstring theory does not imply that that particle is the graviton. The former string theorist Daniel Friedan, one of the early major contributors, is emphatic about this:

³ D. Lüst and S. Theisen, Lectures on String Theory (Berlin: Springer-Verlag, 1989).
⁴ E. Witten, “Reflections on the Fate of Spacetime,” Physics Today, April, 1996.
⁵ B. Zwiebach, A First Course in String Theory (Cambridge: Cambridge University Press, 2004).
In particular, there is no justification for the claim that string theory explains or predicts gravity. String theory gives perturbative scattering amplitudes of gravitons. Gravitons have never been observed. Gravity in the real world is accurately described by general relativity, which is a classical field theory. There is no derivation of general relativity from string theory. String theory does not produce any mechanical theory of gravity, much less a quantum mechanical theory.\(^6\)

Why then do practitioners believe that “string theory is a quantum theory, and, because it includes gravitation, it is a quantum theory of gravity”? How have string theorists arrived at the conclusion that “the harmonious union of general relativity and quantum mechanics is a major success”\(^7\) of superstrings? Moreover, how have they managed to convince other theoreticians of the validity of their explanations? Let us look at another example.

In the abovementioned paper, Scherk and Schwarz also declared that string theory could unify all the fundamental interactions: “If it is, a scheme of this sort might provide a unified theory of weak, electromagnetic, and gravitational interactions.”\(^8\) (These known interactions were then complemented with the strong nuclear force, the latter successfully described by quantum chromodynamics.) This was in 1974. Years later, and after intense work, the proposal had still not been proved. The four-dimensional standard model (it excludes gravity), with all its details, could not be deduced from string theory. In a lecture given at the International Centre for Theoretical Physics (ICTP) in 1986, one of the leading string phenomenologists of the time stated: “Being defined in d=10, some compactification of the six dimensions would be required to make contact with phenomenology. This process is at the moment not understood at all; one has to make crude approximations and then check for consistency a posteriori.”\(^9\) The reason why the process of superstring compactification “was not understood at all” is due to the stringent constrains that supersymmetry imposes on the four dimensional model. As expected from the standard model of particle physics, any physical result with supersymmetry must be renormalizable\(^10\) and requires the existence of chiral spinors.\(^11\) However, there are some difficulties with this: firstly, supergravity\(^12\) with one

\(^6\) D. Friedan, “A Tentative Theory of Large Distance Physics,” [arXiv: hep-ph/0204131].

\(^7\) B. Greene, The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory (New York: W. W. Norton & Co., 1999).

\(^8\) J. Scherk and J. H. Schwarz, “Dual Models for Nonhadrons,” op. cit.

\(^9\) H. P. Nilles, “Supergravity And The Low-Energy Limit Of Superstring Theories,” lectures given at the 1986 ICTP Spring School on Supersymmetry and Supergravity, in B. de Wit et al. (eds.), Supersymmetry, Supergravity and Superstrings 1986 (Singapore: World Scientific, 1986).

\(^10\) In broad terms, this means that the theory cannot contain quantities which take on an infinite value.

\(^11\) Chirality is an essential property of the particles constituting matter: leptons and quarks.

\(^12\) Supergravity is the theory known to be the low energy limit of superstring theory.
supersymmetry is not renormalizable, and, secondly, models with higher numbers of supersymmetries do not include chiral spinors. Satisfying these two conditions is the difficult mission assigned to string phenomenologists. There are several approaches to the problem: the simplest model considers compactification on a multi-dimensional torus, other string theorists prefer to use constructs known as orbifolds or orientifolds; more recently $G_2$ manifolds were tested. Other Calabi-Yau manifolds are currently under examination. Despite this confusing situation, there is one thing string theorists know they must answer: “Why do we live on this particular string vacuum or SSC [superstring compactification]?” This is the most urgent question that needs to be addressed in order to make contact with physical reality. As Michio Kaku writes in the introduction to the 2000 edition of his textbook on elementary string theory: “The search for the true vacuum of string theory is therefore the central theme of this book.” So, if we could explain why the universe chose this particular vacuum we would be able to understand how the standard model arises from superstring theory and why the universe expands as it does. It has been argued by critics that this reformulation of the problem does not solve it. On the contrary, it makes it harder and moves it, dangerously, towards the realm of theology.

In this case, as in the previous case of the quantization of gravity, superstring theorists have been unable to offer an accurate and comprehensive explanation of four-dimensional physics. To be sure, string phenomenology, from the old heterotic string to recent brane models, does not provide the correct value for the quantities associated to the elementary particles known so far. In addition to this, critics emphasize, it does not answer crucial questions that intrigue particle physicists: how is the electroweak symmetry broken? what fixes the masses of the Higgs boson, quarks, neutrinos and charged leptons? what are the sources of the cold dark matter? what produced the big bang? why is there matter-antimatter asymmetry? This state of affairs has lead Sheldom Glashow, an eminent particle physicist, to declare that string

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13 F. Quevedo, “Lectures on Superstring Phenomenology,” [arXiv: hep-th/9603074].
14 Thus, the real problem facing us, in our opinion, is to theoretically settle the following question as quickly as possible: what is the vacuum (ground state) of superstring theory? Since the ground state should correspond to our physical universe, if the true vacuum could be discovered, we might be able to decisively settle whether superstring theory is a theory of the universe or just the latest in a series of failed efforts to discover the Holy Grail of physics, the unified field theory.” M. Kaku, *Strings, Conformal Fields, and M-Theory* (Berlin: Springer-Verlag, 2000), second edition.
15 By the year 2005 there was a vigorous debate within theoretical physics concerning the role of anthropic arguments in determining the real vacuum of the universe. Leonard Susskind’s *The Cosmic Landscape* triggered this passionate debate. The attacks on string theory during that period were unprecedented. For example, Lawrence Krauss, a reputed astrophysicist, wrote that “it is perhaps not too surprising that when one approaches the limits of our knowledge, theologians and scientists alike tend to appeal to new hidden universes for, respectively, either redemption or understanding.” L. Krauss, “Science and Religion Share Fascination in Things Unseen,” *The New York Times*, 8 November 2005. In summary, as Paul Feyerabend would put it, are they scientists or priests?
theory “has failed in its primary goal, which is to incorporate what we already know into a consistent theory that explains gravity as well. The new theory must incorporate the old theory and say something more. String theory has not succeeded in this fashion.”

From the previous examples we have learnt some important things about the development of string theory. Firstly, as research progresses in a given topic, an explicit reference to the unsolved problem tends to disappear from the literature. For instance, we saw how the quantization of gravity is considered by string theorists to be an accomplished task that does not deserve further study, or even a mention. Secondly, while research advances, the initial problem changes in such a way that it becomes increasingly difficult to unravel the convoluted relationship connecting the final problem to the original one. This was illustrated by our second example concerning string theory and the unification of the forces. Originally the idea was to extract the standard model from superstring theory, an investigation encouraged during the second half of the eighties by the promising results obtained from the heterotic string. Then, by the mid-nineties, the goal was to determine the unique vacuum of the mother of all the theories, the M-Theory. And, more recently, the focus was on the right “environment” of the anthropic solution. Things have changed, but the fundamental query remains unsolved: how do we get the standard model from string theory? With these examples we have learnt something else: this occurs while an “outward” discourse (from the “inside” to the “outside” of the professional community) proclaims that the theory has solved such problems. Indeed, in this movement disadvantages have been transmuted into virtues.

In spite of these fundamental flaws in the theory, enthusiasts proclaim that “in string theory all forces are truly unified in a deep and significant way,” or, a bit more prudently, “string theory leads in a remarkably simple way to a reasonable rough draft of particle physics unified with gravity.”

The final outcome of this discourse is the same: the stabilization of string theory as a quantized theory of gravity and unified model. Before concluding this introduction, I would like to add two more quotations. In Zwiebach’s undergraduate textbook he asks:

Why is string theory truly a unified theory? The reason is simple and goes to the heart of the theory. In string theory, each particle is identified as a particular vibrational mode of an elementary microscopic string.

Thus, string theory is a unified theory thanks to its extreme reductionist approach. Brian Greene, in his best-selling book, backs up this statement. Years of hard work have shown that the reductionist approach to string theory is correct.

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16 Sheldom Glashow interview; on the website of The Elegant Universe, http://www.pbs.org/wgbh/nova/elegant/view-glashow.html
17 E. Witten, “Unravelling String Theory,” Nature 438, December, 2005.
18 B. Zwiebach, A First Course in String Theory, op. cit.
These works showed conclusively that numerous features of the standard model—features that had been painstakingly discovered over the course of decades of research—emerged naturally and simply from the grand structure of string theory.\(^\text{19}\)

I think what we have seen in these examples is a characteristic of string theory research and its elaboration of physical reality. At first, a hypothesis is made, explaining openly its significance as well as its difficulties. At this stage no one is sure of the real value of the conjecture, however, it is interesting enough to drive a significant part of the physics community to devote itself to its development. Step by step “evidence” accumulates and after a while the string theory fact emerges. String theorists have created in this way their own nature: a supersymmetric world, a big bang with all the fundamental forces combined, a multi-dimensional universe, and so forth. Although I have provided support to this thesis in the case of the two sanctioned “achievements” of superstring theory, quantization of gravity and unification of the fundamental forces, I will now illustrate in full detail this complex process with another ground-breaking proposal: the AdS/CFT correspondence.

2  A case study: the AdS/CFT correspondence

At the end of 1997, Juan Maldacena, at that time a young researcher at Harvard University, proposed what some physicists consider to be one of the main breakthroughs in the history of string theory and even of theoretical physics. Approaching the physics of black holes with the powerful mathematical tools of superstring theory, he conjectured the existence of a deep relationship between pure non-gravitational theories and superstring theories.\(^\text{20}\) Even though the proposal was not well understood by everybody, it was welcomed and enjoyed rapid acceptance within the community.

This subject has developed with breathtaking speed: Maldacena’s paper appeared in November 1997, yet by the Strings 98 conference...

\(^{19}\) B. Greene, *The Elegant Universe*, op. cit.

\(^{20}\) J. M. Maldacena, “The Large N Limit of Superconformal Field Theory and Supergravity,” [arXiv: hep-th/9711200]. To put it simply, the correspondence says, as it is currently understood, that string theory defined in a negatively curved anti-de Sitter space (AdS) is equivalent to a certain conformal field theory (CFT) living on its boundary. One concrete example is AdS\(_5\)/CFT\(_4\). It states that type IIB superstring theory in AdS\(_5\) is equivalently described by an extended \(N=4\) super-CFT in four dimensions. The other five dimensions of the ten-dimensional space defined by superstring theory are compactified on a five-dimensional sphere, S\(_5\). The five-sphere with isometry group SO(6) is chosen in order to match with the SU(4) R-symmetry of the super Yang-Mills theory defined on the boundary. More complicated models are also possible. Note that there are two different \(N\)’s involved in our discussion: \(N\), in italics, for the number of supersymmetries of the conformal theory, and \(N\), not italicized, for the dimension of its gauge group. For a short introduction to string theory and the AdS/CFT correspondence see, for example, O. Zapata, “String Theory: A Theory of Unification,” [arXiv: hep-th/0612004].
seven months later, more than half the invited speakers chose to
speak on this subject.\footnote{J. H. Schwarz, “Introduction to M Theory and AdS/CFT Duality,” [arXiv: hep-th/9812037].}

Today, Maldacena’s publication is one of the most well-known papers ever
written in theoretical high energy physics.

The first papers submitted to the electronic preprint library citing Mal-
dacena’s conjecture did not delve deeply into the original proposal; they sim-
ply mentioned it in a superficial way. In these papers we find the following
assertions: “It would be interesting to understand the relation between our
arguments and those of [reference to Maldacena’s paper],” and “Maybe an ar-
gument along the lines of [reference to Maldacena’s paper] can be carried out
here as well.” Things changed dramatically when Edward Witten published a
paper formalizing many of the original ideas put forward by Maldacena.\footnote{Another important paper deserving special analysis, what I will do in a next version of this essay, is S.S. Gubser, I. R. Klebanov and A. M. Polyakov, “Gauge theory correlators from noncritical string theory,” [arXiv: hep-th/9802109]. I thank Igor Klebanov for pointing me out this omission.} He
discovered a precise correspondence (here the term “correspondence” is used
for the first time) between string states on the ten-dimensional spacetime,
dubbed the bulk, and operators of the particle physics-like model. He also
computed some scattering processes. To this end Witten identified the bound-
dary of the ten-dimensional bulk with the space where the non-gravitational
particles reside and interact. After this essential contribution, more and more
people started to work on this correspondence.

Here is how Witten referred to Maldacena’s proposal (first lines of the
abstract):

Recently, it has been proposed by Maldacena that large N limits of
certain conformal field theories in d dimensions can be described
in terms of supergravity (and string theory) on the product of d+
1-dimensional AdS space with a compact manifold. Here we
elaborate on this idea and propose a precise correspondence be-
tween conformal field theory observables and those of superg-

\footnote{E. Witten, “Anti de Sitter Space and Holography,” [arXiv: hep-th/9802150].} (Italics added.)

Note Witten’s prudence when referring to it: “It has been proposed.” A
year and a half later Maldacena’s “conjecture” was still a conjecture, that is,
nothing exceptional demanded that its scientific status should be upgraded.
This was the state of affairs in 1999 when a group of leading string theorists,
including Maldacena himself, published a review article on the subject. This
report comprises more than two hundred and fifty pages and is still considered
one of the most complete accounts on the subject.
So, we conclude that \( N=4 \) U(N) Yang-Mills theory could be the same as ten dimensional superstring theory on AdS\(_5 \times S^5\) [reference to Maldacena’s paper]. Here we have presented a very heuristic argument for this equivalence; later we will be more precise and give more evidence for this correspondence.\(^{24}\) (Italics added.)

In the authors’ opinion the correspondence was still in the phase of gathering evidence. It was not yet established as scientific fact. At this point it is worth digressing a moment in order to say a few words about the physics of the correspondence. This will help us to understand its successive evolution towards a higher degree of truthfulness.

AdS/CFT in its strongest version states that superstring theory in the bulk corresponds to a full quantum non-gravitational theory on the boundary of such volume. But, so far support for it has been provided only in the supergravity approximation: the point-like model where the length of the string is equal to zero (\( \alpha' \to 0 \)). In addition, since these computations are also very difficult to carry out, the classical limit is necessary. In this last approximation quantum corrections are discarded (only tree diagrams are considered). The theory is said to be weakly coupled.

The consistency of the theory relies on every operation being done on the gravitational theory having a counterpart on the boundary. (Due to this relationship between what happens in the bulk and on its boundary, the correspondence has been called holographic.) Thus, the supergravity and classical limits must have their corresponding procedure in the boundary theory. Experts have found that this relationship is of the type weak \( \longleftrightarrow \) strong. In short, this means that the easier the computations in the gravitational theory, as in the limits above, the harder it is to find the corresponding non-gravitational results on the conformal field theory side. In turn, when the string calculations are difficult, the boundary computations are easier to perform. This explains why the AdS/CFT correspondence is also often called “AdS/CFT duality.”

After these brief observations, we are now ready to evaluate the following extract from MAGOOG (as the report by Maldacena and collaborators is sometimes labelled):

*One might wonder why the above argument was not a proof rather than a conjecture.* It is not a proof because we did not treat the string theory non-perturbatively (not even non-perturbatively in \( \alpha' \to 0 \)). We could also consider different forms of the conjecture. In its weakest form the gravity description would be valid for large \( g_sN \) [supergravity description with no quantum corrections as explained above], but the full string theory on AdS might not agree with the field theory. A not so weak form would say that the conjecture is valid even for finite \( g_sN \), but only in the \( N \to \infty \) limit (so

\(^{24}\) O. Aharony, S. S. Gubser, J. M. Maldacena, H. Ooguri and Y. Oz, “Large N Field Theories, String Theory and Gravity,” [arXiv: hep-th/9905111].
that the $\alpha'$ corrections would agree with the field theory, but the $g_s$ corrections may not). The strong form of the conjecture, which is the most interesting one and which we will assume here, is that the two theories are exactly the same for all values of $g_s$ and $N$.\textsuperscript{25} (Italics added.)

This passage from MAGOO suggests that in those days many string theorists were not fully convinced of the validity of the correspondence; although something like 1500 papers had already been published on the subject (MAGOO includes 757 references in its bibliography). Despite such wide interest and some important contributions to theoretical physics, the general opinion was that the correspondence was in the process of being proved. In their “Summary and Discussion” the authors concluded saying:

To summarize, the past 18 months have seen much progress in our understanding of string/M theory compactifications on AdS and related spaces, and in our understanding of large N field theories. However, the correspondence is still far from realizing the hopes that it initially raised, and much work still remains to be done.\textsuperscript{26} (Italics added.)

So, by May 1999 string theory experts were convinced that the “simple and powerful observation”\textsuperscript{27} made by Maldacena was in its infancy. At the same time, an optimistic vision was transmitted to young researchers by means of courses and written materials. In a widely used introductory review written by Jens Petersen, which appeared three months earlier than MAGOO, we read:

The Maldacena conjecture [reference to Maldacena’s paper] is a conjecture concerning string theory or M theory on certain backgrounds of the form $\text{AdS}_d \times M_{D-d}$. ... The conjecture asserts that the quantum string- or M-theory on this background is mathematically equivalent – or dual as the word goes – to an ordinary but conformally invariant quantum field theory in a space-time of dimension $d-1$, which in fact has the interpretation of “the boundary” of $\text{AdS}_d$.\textsuperscript{28} (Italicized in the original.)

Similarly, in the written translation of a couple of lectures delivered during the spring of 1998 at The Abdus Salam International Centre for Theoretical Physics, two leading theoretical physicists wrote: “Assuming this conjecture, one can derive results for the large ’t Hooft coupling limit of gauge theory, by

\textsuperscript{25} Ibid.
\textsuperscript{26} Ibid.
\textsuperscript{27} I. Klebanov, “TASI Lectures: Introduction to the AdS/CFT Correspondence,” [arXiv: hep-th/0009139].
\textsuperscript{28} J. L. Petersen, “Introduction to the Maldacena Conjecture on AdS/CFT,” [arXiv: hep-th: 9902131].
doing computations in AdS supergravity.” And concluded, in the last lines, by saying: “Nevertheless, now that we have a precise and better motivated conjecture for the appropriate string in this case, we can hope that progress along these lines will be made in the near future.” Analysis of written publications at that time shows that the veracity of the holographic correspondence was understood by string theoreticians more as a hope rather than as a completed task.

The lines of development for the following three years, from May 1999 to February 2002, were foreseen, and in a certain sense dictated, by Maldacena and collaborators: in chapter 5 they summarized the main results of BTZ black holes and showed how this was related to the boundary theory; in chapter 6, the final one, they focused on QCD-like theories.

Thanks to the great amount of available results on the physics of three-dimensional black holes and a manageable two-dimensional conformal field theory, the AdS$_3$/CFT$_2$ model was for many years the favourite setting for analyzing the correspondence beyond the supergravity limit.

In this paper we study the spectrum of critical bosonic string theory on AdS$_3 \times$ M with NS-NS backgrounds, where M is a compact space. Understanding string theory on AdS$_3$ is interesting from the point of view of the AdS/CFT correspondence since it enables us to study the correspondence beyond the gravity approximation.

Juan Maldacena and Hirosi Ooguri continued working on this framework for some time, arriving at several remarkable results. Unfortunately, the correspondence was not demonstrated beyond the supergravity approximation as first expected. The other main line of research within AdS/CFT was the construction and description of viable QCD-like theories by means of weak gravitational processes.

A fruitful extension of the basic AdS/CFT correspondence [reference to Maldacena] stems from studying branes at conical singularities [references]. Consider, for instance, a stack of D3-branes placed at the apex of a Ricci-flat 6-d cone $Y_6$ whose base is a 5-d Einstein manifold $X_5$.

Even though the two approaches were different, both were trying to provide evidence for the stronger versions of the correspondence. The AdS$_3$/CFT$_2$ effort wanted to prove the exact correspondence in a special case (classical limit

29 M. Douglas and S. Randjbar-Daemi, “Two Lectures on AdS/CFT Correspondence,” [arXiv: hep-th/9902022].
30 J. Maldacena and H. Ooguri, “Strings on AdS$_3$ and the SL(2,R) WZW Model,” [arXiv: hep-th/0001053].
31 I. R. Klebanov and M. J. Strassler, “Supergravity and a Confining Gauge Theory: Duality Cascades and $\chi$SB-Resolution of Naked Singularities,” [arXiv: hep-th/0007191].
with $\alpha' \neq 0$), and the AdS/QCD attempt tried to find plausible phenomenological results. However, by the end of 2001, after four years of intense work and more than two thousand citations to Maldacena’s original paper, the correspondence was still waiting for a definitive proof.

The Berenstein-Maldacena-Nastase (BMN) conjecture was proposed in February 2002 and it rapidly seized the attention of string theorists working on AdS/CFT. This fervent interest on BMN was reflected by the large number of publications that followed. In the month the paper appeared, a fifth of the publications on AdS/CFT was on BMN or at least mentioned it in the main text. The following month, articles on BMN grabbed half the attention of the research on AdS/CFT. A few months later, up four fifths (June and September 2002) of the citations to Maldacena’s 1997 proposal came from the novel BMN conjecture. This rough count clearly shows that the new conjecture was an essential breakthrough within the field. Moreover, as we will see next, it represented the end of a period and the beginning of a new one. After BMN, the truthfulness of the AdS/CFT correspondence changed: it was nearing a scientific fact.

In this new conjecture Maldacena and collaborators envisaged an alternative setting to verify the correctness of the AdS/CFT correspondence beyond the supergravity limit. The idea was to concentrate on a very special case of the original formulation and see how the standard correspondence between string states and operators matched within this new framework. On the bulk side of the correspondence the spacetime background was changed to parallel plane waves. The new condition, pp-waves, was obtained by taking the Penrose limit of the anti-de Sitter space. In the conformal field theory this corresponded to a truncation of the number of operators. It was believed that this new model could shed light on the full quantum correspondence.

It is interesting to see how Berenstein, Maldacena and Nastase referred to the AdS/CFT correspondence, the basis of their new proposal:

The fact that large N gauge theories have a string theory description was believed for a long time. These strings live in more than four dimensions. One of the surprising aspects of AdS/CFT correspondence is the fact that for $N = 4$ super Yang Mills these strings move in ten dimensions and are the usual string of type IIB string theory.\footnote{D. Berenstein, J. M. Maldacena and H. Nastase, “Strings in Flat Space and PP Waves from $N = 4$ Super Yang Mills,” [arXiv: hep-th/0202021].} (Italics added.)

These are the first lines of the paper. Such a presentation suggests that the relationship between gravity and particle physics is a matter of “fact.” They take it for granted. Obviously, there is something paradoxical in all this: what is expected to be proven is at the same time considered true knowledge. But, was this an isolated judgement or rather a belief shared by other string theorists?
Two months after the BMN proposal, Steven Gubser, Igor Klebanov and Alexander Polyakov, collaborating then at Princeton, submitted a paper where it is said:

*It was found* in [reference to Maldacena, Witten, and a previous article by GKP], developing some *earlier findings* of [reference to Polyakov], that the desired string theory in this case lives in the space $\text{AdS}_5 \times S^5$ and that *there is a unique prescription* relating physical quantities in the string and gauge pictures. Many more complicated examples have been analyzed since then, *confirming the existence* of a dual string picture for various gauge theories.\(^{33}\) (Italics added.)

Though the authors confess in the next lines that the correspondence has only been “tested” “mostly in the supergravity limit,” as BMN they also presuppose the full validity of the correspondence. Notice the use of the terms “it was found” and “confirming the existence.” The same predisposition is shown in another important paper written by a group of researchers from MIT and Harvard:

More recently the Maldacena conjecture *has established* a duality between a conformal gauge theory (with a fixed line of couplings) and string theories on an AdS background. However these dualities are well understood only at large values of the gauge coupling [supergravity limit in the bulk].\(^{34}\) (Italics added.)

A widespread trait among publications following the BMN proposal is that the few lines making explicit reference to the AdS/CFT correspondence are often in the abstract or in the first paragraphs. For instance, the well known article by Joseph Minahan and Konstantin Zarembo begins with a very short discussion on AdS/CFT results and limitations. After the six-line review of AdS/CFT, they move on to the main subject of the paper: BMN.\(^{35}\) The function of this brief reference to AdS/CFT in the opening to the paper is simply to contextualize the article; a context that everybody must be familiar with, and accept, in order to proceed further. Post-BMN doctoral dissertations show a similar pattern: the correspondence is assumed and chapters once intended to explain it are systematically dropped. A short section or even several citations now replaced the detailed summary. Another confirmation that the correspondence was entering a new state regarding its factuality is that some

\(^{33}\) S. S. Gubser, I. R. Klebanov and A. M. Polyakov, “A Semi-Classical Limit of the Gauge/String Correspondence,” [arXiv: hep-th/0204051].

\(^{34}\) N. R. Constable, D. Z. Freedman, M. Headrick, S. Minwalla, L. Motl, A. Postnikov and W. Skiba, “PP-Wave String Interactions from Perturbative Yang-Mills Theory,” [arXiv: hep-th/0205089].

\(^{35}\) J. A. Minahan and K. Zarembo, “The Bethe-Ansatz for $N=4$ super Yang-Mills,” [arXiv: hep-th/0212208].
authors did not even consider relevant the citation of Maldacena’s original paper. From the eight most important papers on AdS/CFT published after BMN, only four of them cited it.

What followed in the next years was a confirmation of the previous analysis. As a sample, let us consider the nine most cited articles on AdS/CFT during that period. Three of the papers deal with phenomenological issues and concentrate on the implications of the AdS/QCD duality; that is, the possibility of using the holographic correspondence to obtain precious information on strongly coupled particle physics processes. As stated in one of these papers: “Recently, the gravity/gauge, or anti-de Sitter/conformal field theory (AdS/CFT) correspondence [reference to Maldacena] has revived the hope that QCD can be reformulated as a solvable string theory.” Another three articles focus on a different spacetime background for the correspondence, the Lunin-Maldacena background. This include one written by Oleg Lunin and Juan Maldacena. The other two are by Sergey Frolov and collaborators: “A relative simplicity of the Lunin-Maldacena supergravity background and the \( N=1 \) superconformal theory makes the conjectured duality a new promising arena for studying the AdS/CFT correspondence.” In contrast to the articles on AdS/QCD, these last three are not phenomenologically motivated; rather they try to prove the correspondence beyond a constraining condition called the BPS limit. It is interesting to notice that Lunin and Maldacena called the new proposal “conjecture duality,” while the original AdS/CFT proposal is simply called “correspondence.” This subtlety differentiation suggests that the latter is in a higher, better consolidated, factual level. Another of the nine papers on AdS/CFT concerns integrable models, a subject seeking a solution to superstring theory on non-trivial backgrounds with RR-fluxes. There are two more papers. One proposes a sort of AdS/CFT correspondence for Sasaki-Einstein backgrounds, and the other is about flux compactifications. Strictly speaking, the last article is not about the correspondence; it simply acknowledges the important contribution of the latter to the renewal of the studies on flux compactifications. And it does it in a single line.

Here concludes our short story of the AdS/CFT correspondence. In it we saw how string theorists treated the conjecture when it was proposed for the first time; how they changed their view in the course of time; and how they communicated it to younger members of the community. We discovered that the AdS/CFT conjecture became a fact at the same time as most of the talks

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36 I am considering papers with more than 150 citations on SPIRES (accessed in December 2006).

37 Since it is impossible for a single person to check the hundreds of papers written in that period, January 2005 – December 2006, my discussion only contemplates the nine most cited papers (each with more than 50 citations). This segment of the spectrum will show the main stream of research.

38 J. Erlich, E. Katz, D. T. Son and M. A. Stephanov, “QCD and a Holographic Model of Hadrons,” [arXiv: hep-ph/0501128].

39 S. Frolov, “Lax Pair for Strings in Lunin-Maldacena Background,” [arXiv: hep-th/0503201].
and papers changed the “recently Maldacena conjectured that ...” to “as the AdS/CFT correspondence teaches us ...” and, finally, to the more impersonal “as the AdS/CFT establishes.” We saw how the sentence “Maldacena has recently conjectured that ...” transformed into a single number that pointed to the original paper. Nonetheless this was not imposed, as some interpreters would be inclined to declare, by a “great leader,” nor by the “will of power” of an authoritarian group of researchers, nor by mere convention. Instead, it is the end result of several years of long, hard, and exhausting work. I have sustained that the breaking point was the new “bold” conjecture of BMN, a hypothesis that assumed implicitly the correctness of the old AdS/CFT correspondence. After years spent accumulating “evidence,” but without a definitive proof in sight, there was the desire and need within the community to surmount the old correspondence. The research could safely continue only by protecting Maldacena’s conjecture from profanation, namely, elevating it to the factual level of the more authentic mathematical demonstrations. In another context, the historian of science Steven Shapin wrote: “It was necessary to speak confidently of matters of fact because, as the foundations of proper philosophy, they required protection. And it was proper to speak confidently of matters of fact, because they were not of one’s own making; they were, in the empiricist model, discovered rather than invented.”

To shield the correspondence from attacks was a necessity for the whole community of practitioners. Consequently, more and more discussions on the correspondence were transferred from research papers and PhD theses to graduate and even undergraduate courses. This was the final step towards its final entrance into public lectures and popular science books. Today, the AdS/CFT correspondence pervades the public debate on superstring theory.

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40 S. Shapin, “Pump and Circumstance: Robert Boyle’s Literary Technology,” Social Studies of Science 14, No.4 (Nov., 1984): 481-520.