A Conceptual Analysis of Black Hole Entropy in String Theory

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Aims of the talk

1. To present the **microscopic state counting of the extremal black hole,** performed by Andrew Strominger and Cumrun Vafa in 1996, in its contemporary context.
2. To analyse the argument's rather complex **conceptual structure:** in particular, to identify the various inter-theoretic relations on which it depends (duality and linkage relations).
3. To make clear why the argument was immediately recognised by the string theory community as a successful account of the entropy of this black hole.
4. The subsequent work that it engendered: its relation to the formulation of the AdS/CFT correspondence.
5. Further philosophical questions that the calculation invites: Is the black hole in some sense the same physical system (at different values of the parameters) as the D-brane system to which it is compared? Is the black hole in some sense **emergent** from the D-brane sytem?

Outline

Black Hole Entropy

Recent **empirical discoveries,** using gravitational waves and the Event Horizon Telescope, suggest that black holes exist in nature.

However, we still do not understand many things about black holes: for example, spacetime singularities, the information paradox, and black hole entropy.

Theoretically, a key proposal by Jacob Bekenstein (1973) is that black holes carry entropy (see also Bardeen Carter Hawking), and their temperature was famously calculated by Stephen Hawking (1974).

(See the recent philosophical discussions in: Dougherty and Callender, Wallace, Prunkl and Timpson).

The Bekenstein-Hawking formula for black hole entropy:

$$S_{\text{BH}} = \frac{k_{\text{B}}\, c^3}{4G\hbar}\ \text{Area}$$

Black Holes in Supergravity and String Theory

Black hole solutions in supergravity and string theory had been known since the 1980s (e.g. Gibbons, Hull (1982), Callan, Myers, Perry (1988)).

In 1996, Andrew Strominger and Cumrun Vafa posted a short article on the hep-th with the first microscopic calculation of the entropy of a black hole in string theory.

This provided, in the eyes of many string theorists, a first micropysical account of black hole entropy, and it was taken to confirm the Bekenstein-Hawking entropy formula.

The calculation followed closely a series of key developments in string theory, spawned by Edward Witten's duality conjectures and Joseph Polchinski's D-branes, both of the in 1995.

This microstate counting is perceived by string theorists as one of the major successes of their theory, and it is is among the most highly cited articles in high-energy theoretical physics.

Strominger and Vafa's 1996 Calculation

Strominger and Vafa's calculation also played a key role in developments leading up to the AdS/CFT conjecture.

The Strominger-Vafa result is now 20+ years old and it has been studied by physicists from many different angles, and many different generalisations have been worked out.

We feel that the time is ripe for philosophical and historical analysis of this material.

The Strominger-Vafa (**SV**) paper is a brief statement of a result (11 pages), written during a frantic period of activity in string theory, in which many new key results followed each other in quick succession.

For this reason, I will review some of this material.

Analysing the Strominger-Vafa argument

Our project aims to give a **historical-philosophical analysis of the argument,** and outline its **contemporary role** in string theory and debates on black hole entropy, so as to invite further work on this topic. Two interesting questions here:

(i) Why did Strominger and Vafa's calculation have such **persuasive power** in the mid-1990s, and has continued to do so; so that most string theorists believe that it has provided a microscopic underpinning of the Bekenstein-Hawking black hole entropy formula?

To this aim, we will "factorise" the argument, identifying the inter-theoretic relations (duality and linkage) that it depends on.

(ii) What was its significance for **further developments in string theory** in the (roughly) two years following its formulation, especially the AdS/CFT correspondence?

The argument, in a nutshell

The argument relates four theories, and their corresponding solutions:

1. **Supergravity,** i.e. Einstein's theory of general relativity with specific added matter fields. The black hole is a solution of this theory.
2. A theory of **strings** that interact with higher-dimensional objects called 'D-branes'.
3. A theory describing the dynamics of the **D-branes** themselves.
4. The conjectured **'M theory'** that underlies string theory dualities.

There are conjectured dualities between (the string-theoretic realisations of) (1) and (2), and linkage relations among the others.

The SV paper presents a calculation of the number of microstates of a system of D-branes, i.e. (3) (weakly interacting, short distances).

The calculation is extrapolated and compared to the Bekenstein-Hawking formula for the black hole (1) (strong coupling, large distances).

Assumptions of the argument

There are two main assumptions:

1. Duality between open and closed string theories suggests a close relation between (1) and (3), i.e. the black hole and the D-branes, via (2: strings) (Polchinski).

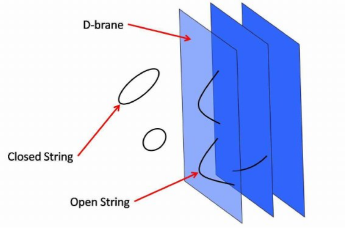
2. Supersymmetry of the various systems justifies the comparison of their entropy at different values of the relevant quantities (distance scale and coupling), because the entropy is guaranteed to be invariant under suitable changes of distance scale and coupling, due to supersymmetry. Thus the black hole is *extremal.*

One of the first generalisations of the argument was to the non-extremal (near-extremal) situation (Callan and Maldacena (1996)).

Part 1. A Bit of String Theory

Open and Closed Strings

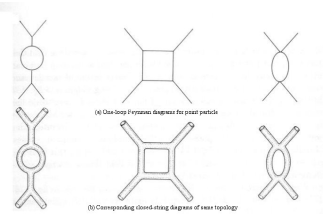
Open strings: have endpoints (on D-branes) and carry non-abelian charges.
D-branes: hyperplanes on which open strings can end. They source the string's non-abelian charges.
Closed strings: carriers of the gravitational force.



Open vs. closed strings correspond, roughly, to the distinction between **nuclear-type forces and gravitational forces.** Fundamental constants:

1. The string length scale, ℓ_s.
Often written in terms of: $\alpha' := \ell_s^2$.
The point-particle limit is: $\alpha' \to 0$.

2. The string coupling constant, g_s.
It measures (quantum) loop effects, i.e. the string theory's expansion in Feynman diagrams.



Introducing jargon

We will consider **'type IIA'** and **'type IIB'** string theories.
They both have open and closed strings, but they differ in the dimensionality of the D-branes.

I will use physicists' jargon **'open string theory'** for 'open string sector of type IIA/IIB theory', i.e. considering the open strings and the D-branes only.

Likewise for **'closed string theory':** closed strings only.

(The jargon is justified (and used) only when open and closed strings "decouple" from each other, i.e. do not interact with each other.)

The semi-classical limit: supergravity

Supergravity theory: a version of general relativity coupled to additional fermionic fields that make the theory supersymmetric.

At low energies (large distances), closed superstring theories are well approximated by semi-classical *supergravity theories*.

Large distances means: $\sqrt{\alpha'}/r \to 0$, where r is the length scale at which the system is probed.

(Thus, strictly speaking, this is a relation between the theories' *models:* which is all we will need. And usually one does not consider the strict limit but just small $\sqrt{\alpha'}/r$. I will continue to use the 'theory' jargon.)

Type IIA/IIB string theories require **ten spacetime dimensions** for their mathematical consistency: thus the supergravity theories are also ten-dimensional. And type IIA/IIB string theories are approximated by corresponding type IIA/IIB supergravity theories.

Two key developments leading up to the Strominger-Vafa calculation (and the 'second string revolution'), both of them in 1995:

The discovery of BPS states in closed string theory

In 1995, Edward Witten gave evidence for a series of **dualities** connecting string theories with each other, and with 11d supergravity.

Key ingredient: a so-far **unknown class of states of closed string theory:** supersymmetric quantum states whose semi-classical limit are **black holes** of supergravity. **Distinctive feature:** their mass is proportional to their electric charge/inverse coupling: $M = c\,|Q|/g_{\rm s}$.

The black holes were already known as 'p-brane solutions' of supergravity (p is the number spatial dimensions of the brane). But it was not known that they are states of closed string theory. Properties:

1. Minimum mass possible for a given charge in supergravity. Thus they **cannot lose energy:** they do not Hawking radiate and have zero temperature. Yet, their entropy is non-zero: their quantum equivalents might be degenerate ground states.

2. Infinitely massive at small coupling, $g_{\rm s} \to 0$: cannot be made of ordinary, weakly-coupled, strings but are rather solitonic states.

Jargon: 'non-perturbative/BPS states' (Bogomol'nyi Prasad Sommerfield).

The (re)discovery of D-branes in open string theory

Polchinski (1995) reintroduced **'D-branes'** in *open string theory* (they had first been defined in 1989). Using the conjectured open-closed string duality, he **identified D-branes with Witten's BPS states.**

> *At the end of Witten's talk, Mike Green and I looked at each other and said 'that looks like D-branes'. It was a shock wave, for me and the rest of the field. I had been living with D-branes for eight years, but never taking it too seriously. But for almost everyone else, it was a new thing: string theory... had D-branes as well (Polchinski, Memories of a Theoretical Physicist, 2017)*

Polchinski's evidence for the identification included:
a calculation of the mass of D-branes agreed with Witten's result, the number of supersymmetries, D-branes couple to the appropriate gauge fields on their world-volume, the charges satisfy Dirac's quantisation condition, the unit of elementary charge correctly accounted for the new set of string theory charges, the numbers of dimensions agreed, and the one-loop amplitude for the interaction between two D-branes agreed.

p-branes and D-branes

The *p*-branes are the supergravity (black hole) solutions that Witten found. They are solutions of the low-energy limit of **closed string theory.**

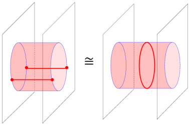
The D-branes are the endpoints of **open strings,** which Polchinski now had shown are related to *p*-branes by open-closed string duality. ('D' stands for Dirichlet, namely the kind of boundary conditions for the strings ending on them).

Polchinski (2017) wrote in his memoirs:

> *As Andy Strominger has reminded me, he, Gary Horowitz and I had lunch together nearly every day for three years, without realizing that their black p-branes [introduced by Horowitz and Strominger in 1991] and my D-branes were the same.*

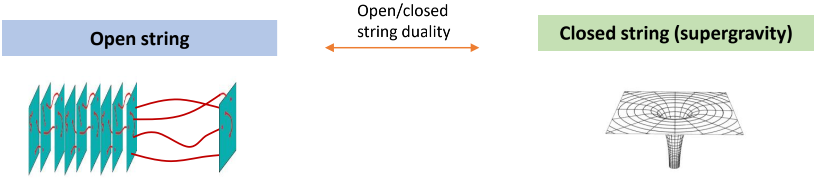
Open-closed string duality

Polchinski's discovery was an extension of **open-closed string duality** (known in perturbative string theory since 1986) to strings on D-branes:



If this approximate duality can be applied to D-branes with black hole (BPS) charges, one gets our two systems of interest:

1. **The open-string D-brane system.**
2. **BPS black hole states** in the supergravity limit of closed strings:

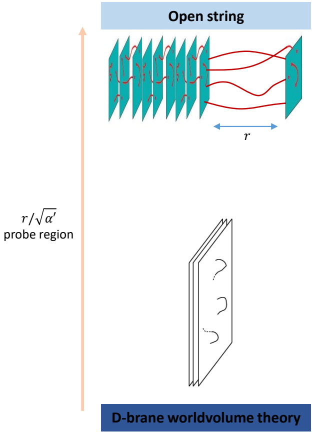


The D-brane world-volume theory

It is interesting to focus on the dynamics **close to the D-branes** rather than the long-distance phenomena (i.e. we probe short distances, $r/\sqrt{\alpha'} \ll 1$, with another D-brane).

Witten (1996) showed that this dynamics is given by a Yang-Mills-type QFT living **on the world-volume of the D-branes.**

It is a *conformal field theory* (CFT), i.e. a locally scale-invariant QFT.



The D-brane world-volume theory and short distances

Douglas, Kabat, Pouliot and Shenker (1997) illustrated the relation between the *world-volume theory* of the D-branes, for various D-branes, and *supergravity*.

For *small probe distances,* the interactions between D-branes (mediated by strings) are described by the *infrared behaviour of the world-volume theory.* Thus **the infrared regime of the world-volume theory describes short distances in string theory.**

This is surprising, since in QFT the infrared regime is usually associated with long distances. It was dubbed the **'IR/UV connection'**. (They ascribe it to the extended nature of the strings between the D-branes.)

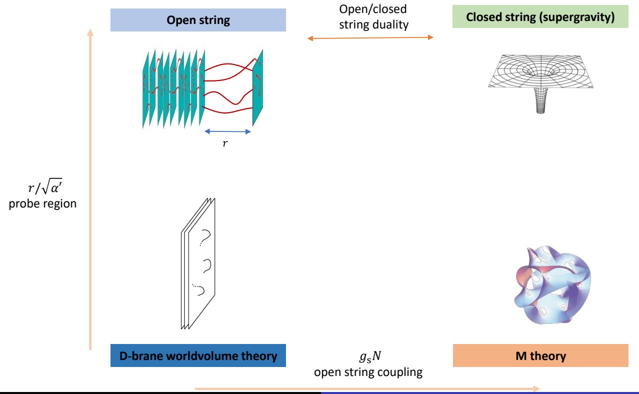
For reasons due to 't Hooft (1974), in the presence of D-branes the relevant string coupling is not g_s, but $g_s N$, where N is the number of D-branes (in what follows, it will be the D-brane charge, Q_F).

Part 2. The Strominger-Vafa Calculation

The Strominger-Vafa Argument

To carry out the entropy calculation, Strominger and Vafa needed to establish a connection between:

(A) The **black hole** solution.
(B) An appropriate **configuration of D-branes,** whose charges are the black hole charges:



(A) The supergravity black hole

The Strominger-Vafa black hole is the **five-dimensional Reissner-Nordström,** extremal black hole. It is a solution of the type IIA supergravity theory on a five-dimensional manifold ($\mathrm{K3}_{4D} \times S^1$):

$$\begin{aligned} \mathrm{d}s^2 &= -f(R)\,\mathrm{d}t^2 + \frac{\mathrm{d}R^2}{f(R)} + R^2\,\mathrm{d}\Omega_3^2 \\ f(R) &= \left(1 - \frac{R_\mathrm{h}^2}{R^2}\right)^2 . \end{aligned}$$

The horizon radius, coupling, and Bekenstein-Hawking entropy (area) are given by the electric charges (two electric fields, F and H):

$$\begin{aligned} R_\mathrm{h} &= \left(\frac{8 Q_\mathrm{H} Q_\mathrm{F}^2}{\pi^2}\right)^{1/6} , \qquad g_\mathrm{s} \sim Q_\mathrm{F}/Q_\mathrm{H} \\ S_\mathrm{BH} &= 2\pi\sqrt{\frac{Q_\mathrm{H} Q_\mathrm{F}^2}{2}} \end{aligned}$$

Valid if: $\tilde{R}_\mathrm{h} \gg \sqrt{\alpha'}$ and $g_\mathrm{s} \ll 1$, which implies: $Q_\mathrm{F}^2 \gg Q_\mathrm{H} \gg Q_\mathrm{F} \gg 1$.

(B) The heart of darkness? The D-brane configuration

The D-brane calculation is **valid if** (different regime):
$g_s \ll 1$ but $g_s Q_F \ll 1$, i.e.: $Q_F \ll Q_H$ and $Q_F^2 \ll Q_H$.

Strominger and Vafa considered a **configuration D-branes in type IIB string theory** on $\mathrm{K3}_{4D} \times S^1$: a combination of D1-, D3-, and D5-branes.

A Dp-brane has a p-dimensional world-volume (plus time).

The three types of D-branes are wrapped on $S^1 \times C$, where C is a cycle (a submanifold) inside K3. (S^1 is large, C is small.)

The D1-brane is wrapped on S^1.
The D3-brane is wrapped on $S^1 \times C_2$ and C_2 is a two-cycle.
The D5-brane is wrapped on $S^1 \times C_4$ and C_4 is a four-cycle.

Thus the D-branes **intersect along a large S^1,** common to all of them.

The connection between the D-brane and black hole systems was made on the basis of Polchinski's identification: the charges of the two systems, the supersymmetries preserved, and type IIA/IIB duality.

The D-brane entropy calculation

After identifying the **configuration** of D-branes that corresponds to the black hole, two steps remain:

(i) Specify the **theory on the world-volume:** the relevant world-volume is the *intersection* between the D-branes: $S^1 \times \mathbb{R}$ (since the $K3$ is small). So, the theory is a **(1+1)-dimensional conformal field theory** (a CFT).

(ii) The **degeneracy of the states** with fixed energy E in a (1+1)-dimensional CFT is given by the **Cardy formula:**

$$d(E,c) \quad \simeq \quad \exp\left(2\pi\sqrt{\frac{Ec}{6}}\right), \qquad \text{for } E \gg c$$

c is the central charge (roughly, the number of elementary degrees of freedom in the CFT). Here the values are (highly non-trivial!):

$$E = Q_{\rm H}\,, \qquad c = 6\left(\frac{1}{2}\,Q_{\rm F}^2 + 1\right)$$

Comparing the results

Thus, after filling in the values of E and c, the Cardy formula gives:

$$S_{\text{stat}} = \ln d(Q_{\text{F}}, Q_{\text{H}}) \simeq 2\pi \sqrt{Q_{\text{H}} \left(\frac{1}{2}\, Q_{\text{F}}^2 + 1 \right)}\ .$$

Strominger and Vafa assumed that the Cardy formula is still valid if $c \gg 1$, i.e. $Q_{\text{F}}^2 \gg 1$, in which case the above matches the **Bekenstein-Hawking entropy formula,** where the area is the area of the horizon of the corresponding black hole:

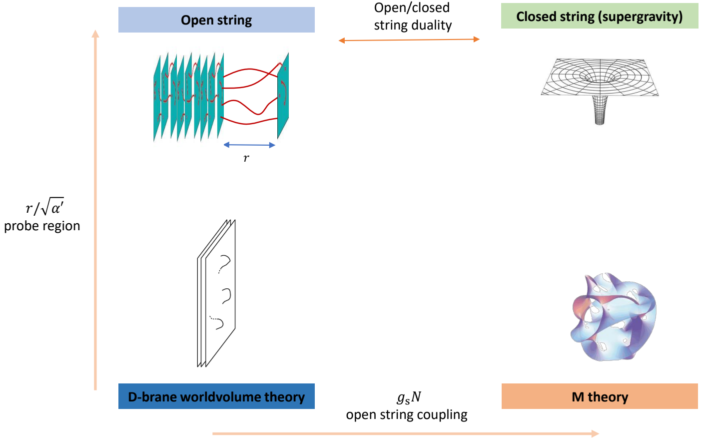
$$S_{\text{BH}} = \frac{\text{Area}}{4G_{\text{G}}} = 2\pi \sqrt{\frac{Q_{\text{H}} Q_{\text{F}}^2}{2}}\ .$$

This is the **Strominger-Vafa result,** relating the Boltzmannian entropy for the D-branes to the Bekenstein-Hawking entropy.

Supersymmetry/topology guarantees that, in addition to taking $c \gg 1$, one may extrapolate from $g_{\text{s}} Q_{\text{F}} \ll 1$ to $g_{\text{s}} Q_{\text{F}} \gg 1$
(the number of BPS states is independent of the 't Hooft coupling).

Analysis of the argument

The derivation depends on linking the strongly coupled supergravity description with the weakly coupled D-branes: due to supersymmetry, the degeneracy of the D-branes is independent of this variation. (Hartman, Keller, Stoica 2014 prove that the Cardy formula is valid if $c \gg 1$). The calculation is summarised thus:



M Theory

In the bottom-right, M theory corner, is a theory that should be valid at small distances and strong coupling. But this theory is unknown.

Witten (1995) made some conjectures about what this theory could be like. He argued that, at strong coupling, type IIA string theory "develops an 11th dimension", and becomes eleven-dimensional supergravity.

But eleven-dimensional supergravity is not yet the full M theory: it is only its classical, low-energy limit.

M theory did not play a role in the Strominger-Vafa argument, except as guidance (and motivation).

The Strominger-Vafa result further motivated a number of approaches to M theory (see below).

Idealisations

Two idealisations on which the argument depends:

1. **Supersymmetry:** the black hole is extremal because of the supersymmetry of the states (BPS states). But the black holes that we observe in the universe have small or zero charge. To increase the physical relevance of black hole entropy calculations, it is desirable to go away from extremality.
   But even if one would not succeed in doing the zero-charge case, the near-extremal case is already theoretically interesting.
2. **Higher dimensions:** the Strominger-Vafa black hole is five- not four-dimensional. If the calculation only worked out in five dimensions, this would be a good reason to question its generality and salience.

Did subsequent work go beyond these assumptions?

Generalisations: near-extremal black holes

Callan and Maldacena took, in 1996, a five-dimensional black hole with mass M **exceeding the extremal value,** M_e, by a small amount δM:

$$M = \frac{3\pi}{8G_{\mathrm{N}}}\left(r_+^2 + r_-^2\right) = M_e + \delta M = |Q| + \delta M$$

Despite the breaking of supersymmetry, **the microscopic and macroscopic calculations agree:**

$$\begin{aligned} \frac{\delta S}{S_0} &= \frac{3}{\sqrt{2}}\sqrt{\frac{\delta M}{M_e}} \\ T_{\mathrm{H}} &= \frac{2}{\pi r_e}\sqrt{\frac{\delta M}{2M_e}} \end{aligned}$$

They also calculated the *radiation rate,* which confirms the black-body spectrum predicted by Hawking. The mechanism for evaporation is that open strings on the D-brane collide to form closed strings, which are then detached from the D-brane.

Generalisations

Four-dimensional black holes. Maldacena and Strominger (1996) and Johnson, Khury and Myers (1996) derived the entropy of the four-dimensional Reissner-Nordström extremal black hole. It carries four charges:

$$S_{\rm BH} = 2\pi\sqrt{Q_2 Q_6 nm}$$

Again, the derivation agrees with the microscopic calculation, using Cardy's formula.

Other successful generalisations

Rotating black holes, i.e. black holes with mass, charge, and spin.

Black holes in M theory. Maldacena, Strominger, and Witten (1997) used the world-volume theory of an M5-brane in eleven dimensions to calculate the entropy. They compared this to a supergravity calculation for the corresponding black hole, corrected by a one-loop quantum correction.

AdS-CFT. The Strominger-Vafa calculation was a crucial step in the development of gauge-gravity dualities. The calculation itself can be reproduced and generalised in AdS-CFT, including for non-extremal situations (e.g. BTZ black holes etc.).

Since then, there have been very many generalisations: a huge field!

Part 3. Further questions about the Strominger-Vafa black hole

Further philosophical questions that the calculation invites:

Is the black hole in some sense the same physical system (at different values of the parameters) as the D-brane system to which it is compared? Is the black hole in some sense emergent from the D-brane sytem?

Cautious and pessimistic points of view

Smolin (2006) dubbed the view that the two models describe different systems, the "pessimistic point of view": 'the relationship between the two systems is probably an accidental result of the fact that both have a lot of extra symmetry.'

While he calls the Strominger-Vafa result 'perhaps the greatest accomplishment of the second superstring revolution', he wonders whether 'a genuine explanation of the entropy and temperature of black holes' had been provided, since 'the piles of branes are not black holes, because the gravitational force has been turned off.'

Jacobson voiced similar reservations (in connection with the black hole information paradox not the counting itself): 'Before AdS/CFT, there was this wonderful state-counting, but the connection for me with black holes was really indirect, because they were weak coupling phenomena, and there wasn't actually a black hole there, it's just a stack of D-branes. If you turn the coupling constant up non-renormalisation theorems from supersymmetry tell you that the state counting result must be preserved' and thus one could 'make a black hole'.

Stringy black holes and loop quantum gravity

Rovelli (2013) compared the string result to a similar result in loop quantum gravity:

'Black holes thermodynamics is definitely a success of string theory, and in my opinion, the strongest evidence for its physical relevance. A similar success can be claimed by loop gravity. Both successes are partial in my opinion. The string derivation is still confined to, or around, extreme situations, as far as I know, and since it is based on mapping the physical black-hole solution into a different solution, it fails to give us a direct-hand concrete understanding of the relevant black hole degrees of freedom, as far as I can see. The loop derivation of black hole entropy gives a clear and compelling physical picture of the relevant degrees of freedom contributing to the entropy, but it is based on tuning a free parameter to get the correct Bekenstein-Hawking entropy coefficients, and this does not sound satisfactory to me either.'

How are the two systems related?

What arguments are there that could relate the two systems, rather than just the entropies?

If there was a duality between the open and closed subsectors of the superstring, this might be a reason to argue that the black hole and the set of D-branes is the same system, at different values of the coupling.

But we share some of the previous caution: for there are only perturbative definitions of the superstrings and, to the best of our knowledge, the present consensus is that an exact duality between open and closed strings is *not* to be expected, *in the Strominger-Vafa example.* (This consensus is not fully established, and some still hope that a duality might after all be found.)

In general, a duality is only expected when ‘there is a complete decoupling of the supergravity description from that of the gauge theory’ (Johnson, 2003). String theorists realised in 1997 that this decoupling happens in the near-horizon limit in the black hole spacetime. This leads to Maldacena's AdS/CFT.

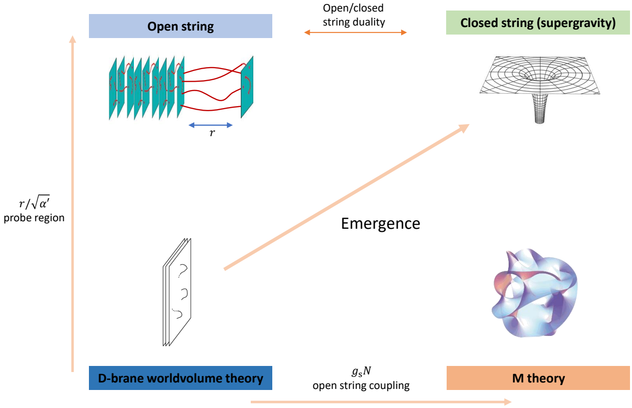
Emergence of the black hole?

The semi-classical gravity description might be interpreted as an approximate, 'macroscopic' description that emerges from the 'microscopics' as we change the parameters.

There are various suggestions along these lines in the physics literature: the black hole's charge should be considered as due to D-branes, since these 'actually are the *basic sources* of the fields'; the p-brane is ' "made of D-branes" in the sense that it is actually the field due to [the D-branes], all located at $r = 0$' (Johnson 2003).

Johnson also suggests that the D-branes, extrapolated to strong coupling, should be thought of as *parts, or as being constituents, of* the black hole.

This suggests that the theories can be related by an *emergence relation*, as follows:


Open string
Open/closed
string duality
Closed string (supergravity)
r
$r/\sqrt{\alpha'}$
probe region
Emergence
D-brane worldvolume theory
$g_s N$
open string coupling
M theory

Emergence of the black hole

In the philosophical literature, there is a widespread view of emergence as a "delicate balance" between *dependence,* linkage or rootedness, and *novelty,* or autonomy.
(There are of course several other notions of emergence, but this one suffices.)

In addition, the literature sees the *physically significant* cases of emergent behaviour as those in which the linkage relation is *robust,* i.e. the emergent behaviour is relatively insensitive to the details of the bottom level.

One can interpret the supergravity black hole solution, which is macroscopic (top level) as **emergent from** the configuration of D-branes (microscopic, bottom level).

Emergence of the black hole

The **linkage relation** involves changing the coupling and scale, which implies taking large charge Q_F, i.e. large entropy/large number of degrees of freedom (plus an approximate duality).

While doing this, there is **numerical agreement of "universal quantities':** entropy, mass, and charge.

There is also **novel behaviour:** the black hole is a gravitational system, while the D-brane is not. (More on this below).

It is also **robust:** since the properties of the black hole are independent of the details of the microscopic theory: e.g. the location of the open strings on the D-branes.

Novelty, in more detail

But as I hinted at before, it is not enough that some quantities agree between the two systems, in order to claim that a black hole emerges.

For a *black hole* to emerge, its *metric* should appear from the linkage relation. This would be true novelty—to get the black hole metric out of a non-gravitational system.

If string theory is consistent, something like this should work: after all, D-branes give a good description of interacting open strings, and the latter are related—at least in perturbation theory—to supergravity, which is the low-energy limit of closed string theory, and the black hole is one of its solutions.

If these assumed inter-theoretic relations are correct, then there should be at least a perturbative match between the black hole metric and an appropriate quantity in the world-volume theory of the D-branes.

Where is the black hole metric?

The appropriate candidate for such a quantity is the ‘effective moduli space of the D-brane system’, i.e. the geometry of the field space in which the D-brane world-volume fields take place, which, under the duality, are reinterpreted as spacetime coordinates. This space comes with a metric, which is reinterpreted as the black hole metric.

Does this work, or is it just words?

Emergence of the black hole metric

Douglas, Kabat, Pouliot and Shenker (1996) and Douglas, Polchinski and Strominger (1997) developed methods to calculate moduli space metrics from configurations of D-branes. Following the approximate open-closed string duality, these metrics were then reinterpreted as black hole metrics.

They calculated the effective action of the motion of a D1-brane in the background of a D5-brane. From the action they read off the D-brane moduli space metric, order by order in the loop expansion in the D-brane world-volume theory. They found agreement with the black hole metric of Strominger and Vafa for the tree-level and one-loop terms at large distances (i.e. for small values of $\sqrt{\alpha'}/r$). .

Alarmingly, they found disagreement at two loops, i.e. at order α'^2/r^4 in the metric (this term was zero). But Juan Maldacena, in a lecture at *Strings '97* in Amsterdam, reported that the D-brane action had the right structure, and the two-loop term was **non-zero** and would also work out. He was at the brink of discovering AdS/CFT.

Emergence and AdS/CFT

As far as we can tell, no one finished that calculation, perhaps because everybody believed it would work out, and attention went to the related problem of AdS/CFT.

Ultimately, the natural goal of such reconstruction efforts would have been to recover the *entire* black hole metric from the D-branes (with quantum corrections), and not just the region close to the black hole/horizon. But one only expects the metric in the near-horizon region to agree with supergravity.

This led Maldacena to intuit AdS/CFT, which followed from studying the near-horizon region of the same D1-D5 system.

In AdS/CFT, it was shown that the bulk fields can be reconstructed from CFT data, and systematic methods were developed to get the bulk metric and matter fields from the correlation functions of the CFT (De Haro, Skenderis and Solodukhin, 2001).

Summary and Conclusion

1. The Strominger-Vafa result raises a wealth of interpretative issues that urgently need philosophers' and historians' attention.
2. The literature suggests that the relation between the black hole and the D-branes is not (exactly) a duality, as it is conjectured to be in AdS/CFT.
3. We have proposed that, based on the evidence, that relation is best construed as the emergence of a macroscopic system from a microscopic system, as we increase the 't Hooft coupling (number of D-branes) and probe the system at larger distances.
4. However, any statement about the ontology of the black hole states could not be final, since the status of the open-closed string duality is undecided.

Thank you!