String Junctions and Bound States of Intersecting Branes

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Abstract

We study four-dimensional black hole configurations which result from wrapping M5-branes on a Calabi-Yau manifold, as well as U-dual realizations. Our aim is to understand the microscopic degrees of freedom responsible for the existence of bound states of multiple branes. The details depend on the chosen U-frame; in some cases, they are massless string junctions. We also identify a perturbative description in which these states correspond to twisted strings of intersecting D3-branes at an orbifold singularity. In each case, these are the preponderant states of the spacetime infrared conformal field theory and account for the entropy of the blackhole.

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1 Introduction

It is by now well-known that systems of intersecting branes correspond to blackholes, and the entropy of such a system may be accounted for by enumerating string states \[1\]. At least when sufficient supersymmetry is preserved, the configuration of branes is a bound state at threshold. In many cases, these bound states signal the existence of degrees of freedom localized on the intersection manifold. It will be the aim of this note to understand in more detail the nature of these new states.

We are interested here in an intuitive problem: what is the detailed mechanism for binding together a collection of many (more than two) branes, and in particular, what are the relevant microscopic degrees of freedom? For a bound state of a pair of branes, we can certainly expect that ordinary strings stretching between them are responsible for the binding. However, in intersections of more than two branes, binding by ordinary strings cannot account for the entropy of the configuration, as we will discuss in some detail below.

The system that we will have in mind throughout this paper is the four-dimensional blackhole obtained from an M5-brane wrapped on a divisor of a Calabi-Yau threefold. However, it will be useful to consider directly a collection of three types of M5-branes wrapped on orthogonal cycles of a \(T^6\). In much of the paper, we will discuss directly the case of \(T^6\), although we explore Calabi-Yau’s in the final section. In the case of \(T^6\), we may take the M5-branes to be arranged as follows:

| Brane | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|---|
| \(M_{51}\) | - | - | - | - | - | - | - | - | - | - |
| \(M_{52}\) | - | - | - | - | - | - | - | - | - | - |
| \(M_{53}\) | - | - | - | - | - | - | - | - | - | - |
| \(P_L\) | - | - | - | - | - | - | - | - | - | - |

The four-dimensional blackhole has an \(E_{7,7}\) U-duality group; a useful diagonal basis identifies four charges as the number of M5-branes of each of three types plus momentum along the eleventh direction. The entropy of this blackhole is given, at least to leading order, by the product of these charges, and may be thought of as counting all of the excitations of the blackhole.

Let us briefly review what is known about this system. There are several points of view. In the limit where the compact manifold is small, one attains an effective description in terms of a 1+1-dimensional field theory on the intersection manifold of the M5-branes. This theory is a superconformal
field theory in the infrared, with (0, 4) supersymmetry. First, there is an important analysis of Ref. [2] (see also Ref. [3]) which computes the central charge of this theory in terms of the cohomology of the complex divisor upon which the M5-branes are wrapped. Thus the entropy is computed, in leading order, by the triple-self-intersection number of the divisor. This number can be thought of as the number of free fields required to describe the entropy of the system. String states stretching between two types of branes would only account for double intersections, and thus fall short. To our knowledge, a concrete proposal for the target space of a $\sigma$-model has not been given, although perhaps intuitively one expects that this then is related to the complexified moduli space of the divisor. Whatever this spacetime CFT is, it is known that on $T^6$ it must have a moduli space of deformations given by $F_4(4)(\mathbb{Z}) \backslash F_4(4)/Sp(2) \times Sp(6)$.\\

The low energy physics of the bound states may be understood in terms of deformation theory. Locally, we can discuss the triple intersection in $\mathbb{C}^3$, coordinatized by $z^1, z^2, z^3$. An equation for the divisor is of the form

$$P_{N_1,N_2,N_3}(z^1, z^2, z^3) = 0 = P_{N_1}(z^1)P_{N_2}(z^2)P_{N_3}(z^3) \quad (1)$$

where $N_i$ are the degrees of each polynomial. The zeroes of this polynomial correspond to the position of each M5-brane. The holomorphic deformations of the divisor are of the form

$$P_{N_1,N_2,N_3}(z^1, z^2, z^3) + Q_{N_1-1,N_2-1,N_3-1}(z^1, z^2, z^3) = 0 \quad (2)$$

The degrees of the polynomial $Q$ have been chosen such that this deformation does not alter the asymptotic form. The deformations are localized at triple intersections. To see this, fix $z^{1,2}$ very large away from the zeroes of the polynomial; it is then clear that the third variable will be very small. That is, the deformations can only be large when $z^{1,2}$ are close to the zero of their respective polynomial; this may be verified explicitly.

We can choose to write the deformations in the following form:

$$Q_{N_1,N_2,N_3} = \sum_{i,j,k} a_{ijk} \frac{P_{N_1}(z^1)P_{N_2}(z^2)P_{N_3}(z^3)}{(z^1 - r^1_i)(z^2 - r^2_j)(z^3 - r^3_k)} \quad (3)$$

The $a_{ijk}$ are the localized deformations, and appear as fields in the low energy description. The number of degrees of freedom then is simply counted as the number of triple intersections; because of supersymmetry, these must come in
supermultiplets, with \( c = 6 \). When we compactify, care must be taken with boundary conditions, and so not all of these deformations are allowed. One expects, however, that these effects are subleading compared to the number of triple intersections. We will see evidence of this below.

Furthermore, the near-horizon limit of this blackhole displays geometry \( AdS_3 \times S^3/\mathbb{Z}_N \times M_4 \); the supergravity spectrum on \( AdS_3 \) has been computed, and recently, the quantization of strings in this background has been considered. In this paper, we are not directly interested in such SCFT descriptions. Instead, we would like to elucidate the microscopic stringy physics responsible for the existence of the boundstate. The physics that we are interested in will appear quite different from the point of view of different U-dual frames. We discuss several different U-frames here; perhaps the most intuitively appealing picture is within a Type IIB frame, where the binding of three branes is related to the existence of massless string junctions localized at the triple intersection. The identification of these non-perturbative states is hampered by the absence of BPS states in this background, although we give strong arguments for the existence of the boundstates. Another Type IIB frame involves intersecting D3-branes localized at an orbifold singularity; the bound states are understood in terms of twisted strings. The latter frame leads to a perturbative UV gauge theory description of this system.

2 String Junctions

We begin with a short review of the essential properties of string junctions. In Type IIB string theory, 1-branes are classified by a pair of integers \((p, q)\). In this notation, the fundamental string is a \((1, 0)\)-brane, and the \(D1\)-brane a \((0, 1)\)-brane. It is known that, subject to some conditions, there is a BPS state consisting of three such branes meeting at a junction. Since \( p \) and \( q \) are the charges with respect to the 2-forms \( B_{NS} \) and \( B_{R} \), they must be conserved at the vertex:

\[
\sum_i p_i = \sum_i q_i = 0. \tag{4}
\]

In addition, there is a condition on the tensions of the branes, and this condition depends on the string coupling.

Now note that there is a U-duality frame in which the 3 M5-branes become an NS5-brane, a D5-brane and a D3-brane in Type IIB string theory. This is
attained (refering to the table in Section I) by compactifying the 10-direction, then performing T-duality along, say, the 2-direction. These three branes intersect along a string as did the M5-branes. The low energy theory then is expected to be a 1 + 1-dimensional CFT with (0, 4) supersymmetry.

| Brane | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------|---|---|---|---|---|---|---|---|---|---|
| $D3$  | ● | ● | – | – | ● | – | – | – | – | – |
| $D5$  | ● | ● | ● | – | ● | ● | – | – | – | – |
| $NS5$ | ● | – | ● | ● | ● | ● | – | – | – | – |
| $P_L$ | – | – | – | – | – | – | – | – | – | – |

It is well known that fundamental strings may end on D-branes, and by S-duality, the D1-brane may end on the NS5-brane. Since the D3-brane is S-invariant, any $(p, q)$-1-brane may end on it. Thus, at least from the point of view of charge conservation, the state shown in Figure 1 exists. Furthermore, the string junction is massless when the three branes intersect; the junction may be made massive by moving the branes away from each other in the 789-directions.

Now, each of the ends of the string junction may terminate on any of the $N$ branes of the appropriate type. Thus, we see that there are of order $N_1N_2N_3$ states present here. Furthermore, since the junction must organize itself into a representation of the (0, 4) supersymmetry, there are $4N_1N_2N_3$ bosonic states and their superpartners. String junctions then account for the entropy of this configuration. Note that in this frame, open string states stretching between branes are not this numerous. Thus, at least to leading order, the entropy is accounted for by non-perturbative states.

![Figure 1: Cartoon of junction between branes.](image-url)
There are several potential problems with this picture however, and we now turn to a discussion of the relevant issues. We have claimed above that the string junctions are massless when the branes intersect. Although this is clearly true geometrically at the classical level, it is not true that the mass of a massive state is protected. To understand the relevant issues, we should consider the details of (0, 4) supersymmetry algebra in two dimensions.\[8\]

The algebra takes the form

$$\{Q, Q\} = P_R$$  \hspace{1cm} (5)

In particular, there are no central charges as that requires both left and right moving supersymmetries. The BPS bound is thus simply $P_R \geq 0$; the only states saturating the bound are massless and may have $P_L \neq 0$. This implies that in any ultraviolet description, only the massless states with $P_R = 0$ will necessarily survive down to the infrared conformal theory and contribute to the entropy of the configuration we are studying. For this massless state to be present then, we must argue that the classical moduli space is unmodified quantum mechanically, at least at the origin. Indeed, we do not expect such modifications because of the (0, 4) supersymmetry. This is actually more restrictive than (2, 2); for example, the metric of the target space manifold must be hyperkähler. Further evidence will be presented below.

If we identify the states localized at the intersection to be of a non-perturbative origin (at least in this frame), then we must become comfortable with the idea that the conformal field theory of ordinary string states is somehow insufficient. Indeed, we can think of this situation as akin to a conifold singularity–at the origin, there is a new branch of the moduli space, parameterized by vev’s of the fields corresponding to string junctions. This is not obviously inconsistent, as near the NS5-five branes the string theory is strongly coupled which invalidates perturbation theory.

In the next section, we consider a different U-frame, in which these states appear in the perturbative spectrum.

### 3 The Orbifold Frame

In this section, we discuss another U-frame which is perturbative, and the localized states at the intersection are twisted strings. To attain this, we may begin with the configuration of the last section, and perform a T-duality along $X^{1,2}$:
The interpretation of this configuration is that of a pair of D3-branes intersecting along a line ($X^6$), at a $\mathbb{Z}_{N_3}$ orbifold singularity. Here, $N_3$ is the number of NS5-branes in the original picture, and there are $N_1$ ($N_2$) D3-branes of each type. Note that in this frame, there is no manifest triality between $N_1$, $N_2$ and $N_3$. This occurs simply because of taking a definite U-duality frame; triality will be recovered in U-invariant quantities, such as the entropy.

This is an interesting configuration in its own right. There has been several appearances of D3-branes at orbifold singularities in the literature, giving rise to interesting 3 + 1-dimensional gauge theories. In the present configuration, we find a gauge theory description of the 1 + 1-dimensional intersection. This theory is an ultraviolet description where gravity has been decoupled, which will flow to the relevant conformal field theory in the infrared. In this theory, we will be able to identify the states that are localized at the intersection, and which contribute the predominant amount of entropy. Since the configuration is perturbative, the analysis is reliable. Furthermore, we will be able to map these states to the string junctions of the previous section.

The spectrum of this gauge theory may be obtained via a straightforward application of familiar techniques. Note first that if we concentrate on the states of a single D3-brane but dimensionally reduce along a two torus, we expect to see multiplets of (4, 4) supersymmetry. The supersymmetry preserved by each of the two D3-branes is incompatible, and at the end we are only left with (0, 4) supersymmetry; the string states connecting $D3_1$ to $D3_2$ do not form full (4, 4)-multiplets. In fact, we will find that the orbifolding acts as to shift the gauge quantum numbers of fermions with respect to those of bosons.

To construct the spectrum, account for the orbifolding by $N_3$ images of the collections of $N_1$ ($N_2$) D3-branes. String states that stretch between D3-branes of the same type, as mentioned, give multiplets of (4, 4) supersymmetry—the fermions and bosons are in the same gauge multiplets.

\[\begin{array}{c|cccccccccc}
\text{Brane} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
D3_1 & \bullet & – & \bullet & \bullet & – & – & \bullet & – & – & – \\
D3_2 & \bullet & – & \bullet & – & \bullet & \bullet & – & – & – & – \\
KK5 & \times & \bullet & \bullet & \bullet & \bullet & \bullet & – & – & – & – \\
\end{array}\]

\[\text{In the table, the symbol} \times \text{refers to the Taub-NUT direction. We take} X^{1,7,8,9} \text{to be noncompact. This ensures that the singularity is isolated.}\]
Those multiplets which correspond to string states between branes at the same image, turn out to be hypermultiplets, whereas those stretching horizontally (see Fig. 2) are vector multiplets, (this nomenclature comes from looking at the four dimensional theory on the intersection of two D5-branes, where the vector directions are along the intersection manifold, and the hypermultiplet directions are orthogonal). The resulting gauge group is then

$$\prod_{k=1}^{N_3} [U(N_1) \times U(N_2)].$$

(6)

The string states that stretch between D3-branes of different type however are acted upon non-trivially by the orbifold. It should be noted that the $\mathbb{Z}_{N_3}$ acts chirally on the $SU(2) \times SU(2)$ R-symmetry on either of the D3-branes. There are several reasons for this choice. First, this particular orbifold action is important for preserving $(0,4)$ supersymmetry and the resulting hyperkähler structure. More importantly, the corresponding 4-dimensional blackhole is, as in Ref. [4], related to a configuration of NS5-branes and KK monopoles, for which the near-horizon geometry is given by $AdS_3 \times S^3 / \mathbb{Z}_{N_3}$. In the near-horizon region, the orbifold of the sphere indeed acts chirally. This is no coincidence; in fact both the near-horizon geometry, as well as this gauge theory description, share the same geometrical features. The gauge theory, then, is an ultraviolet description of the spacetime conformal field theory which controls the physics of the near-horizon region of the blackhole. The detailed form of this CFT, as mentioned, is not known; however, at the very least, the gauge theory discussed here should be capable of reproducing some of the features of the CFT, in particular the chiral ring. We do not attempt to demonstrate this here.

Given this orbifold action, bosons and right moving fermions form supermultiplets, and the left moving fermions are singlets under supersymmetry. The field content is summarized in Fig. 2. The fields are supermultiplets for the vertical lines, and left-moving fermions for the diagonal lines. The nodes and edges have a supermultiplet and left-moving fermion singlets, as is required in order to complete representations of $(4,4)$ supersymmetry. Note that this portion of the spectrum is an example of “misaligned supersymmetry” of Ref. [3], as bosons and fermions are degenerate but they are in

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2We consider the low energy ultraviolet theory, and so do not concern ourselves with the possible decoupling of $U(1)$'s.

3Note that in order to check non-chiral operators, we would need to control the non-perturbative details of the gauge theory in the infrared limit.
different representations of the symmetry groups. Thus much of the structure of a (4, 4)-supersymmetric theory is present; only the gauge representations are aware of the breaking to (0, 4).

Figure 2: A portion of the quiver diagram. The open (closed) circles represent images of the $N_1$ ($N_2$) collections of D3-branes. Bosonic string states and superpartners are represented by dashed lines, left-moving fermions by solid lines.

As the configuration is made only out of D3-branes, the value of the type IIB coupling constant is not fixed at any value, and we can actually take a weakly coupled limit, so that the field theory analysis is accurate.

Next, we would like to count (gauge invariant) modes, in order to probe the entropy of the corresponding blackhole. To facilitate this, we move on the moduli space to a generic point, where the gauge group is broken as much as possible. To this end, we move all D3-branes apart in the 2345-directions (but not away from the orbifold singularity). The gauge group is Abelian, $U(1)^{N_1} \times U(1)^{N_2}$, and massless charged states are present. While most of the (4, 4) vectors and hypermultiplets have been lifted, the twisted states survive. These states are localized at the orbifold singularity, and have multiplicity $N_1N_2N_3$ (since they are in $(N_1, \bar{N}_2)$ representations, and there are $\bar{N}_3$ images). For each of these, we have two complex bosonic modes and two complex fermionic modes (as in Fig. 2). In a sector with fixed $P_L$, these states dominate the entropy, giving by a standard argument $S =$
\[ 2\pi \sqrt{6N_1N_2N_3P_L + \ldots} \]

It was found in Ref. [4] that the central charge of the spacetime conformal theory contains no subleading corrections. However, in the present construction, it appears that there is a problem. There are massless fields which are the remnant of the adjoint hypermultiplets. There is one such supermultiplet remaining per vertex of Fig. 2, and thus one would expect that these fields contribute to the entropy at order \((N_1 + N_2)N_3\). It is possible that the correct central charge is nevertheless obtained as follows, by canceling this contribution. We have assumed that all triple intersections contribute an independent supersymmetric degree of freedom to the entropy, but this is not really true, as not all of the local deformations can produce a smooth manifold. This means that some fraction of the (vertical) fields have a superpotential and therefore do not contribute to the entropy. It is quite possible that this correction to the leading term in the entropy above precisely cancels the effect of the adjoint fields. A similar mechanism is known to occur in the D1-D5 system [10, 11]–the dimension of the moduli space is smaller than the number of fields because of D-term constraints (in our case we have F-terms). It is clear then that the present description is far from being a free CFT, at least at finite \(N\). The gauge theory description is useful however in the long string limit, where these effects are subleading. A useful application would be the computation of the chiral ring.

### 3.1 Relation to String Junctions

Now note that we expect that this discussion of the spectrum is robust– the entropy is accounted for by twisted string states, as long as the singularity itself is not modified by quantum corrections. Furthermore, this description of the states localized at the intersection is T-dual to the description in the previous section in terms of string junctions, this is, from one description to the other we do a discrete Fourier transform. We regard this then as definitive evidence (if duality is to be believed) for the existence of massless string junctions in that frame, and hence for their contribution to the entropy.

### 4 Other U-frames

It is of interest to consider other U-frames in the same context. We confine ourselves to brief discussions of three such frames; in most cases, an
understanding of the localized states is considerably more difficult.

4.1 M-theory and 3 M5-branes

First, we consider the original M-theory configuration, and account for the entropy there. This may be understood by beginning with the string junction; if we lift this to M-theory, we find that the junction becomes a M2-brane "pants section". Each \((p,q)\)-leg has one direction wrapped along the vector \((p,q)\) in the \(X_2^{10}\) torus. Thus the bound state degrees of freedom are these pants sections; at a triple intersection point of the M5-brane, they have zero area and so should go massless. A smooth point in moduli space then is attained by turning on vevs for these low energy fields.

4.2 Type IIA and the 4440-system

By compactifying the M-theory configuration along \(X^6\), we obtain a system of three different types of D4-branes, plus D0-branes from momentum along \(X^6\). This is a system that has been well-studied in the blackhole context. The pants section of the preceding paragraph descends to a similar D2-brane, while the momentum descends to a constant D0-flux through the D2-brane, \(F_2 = P_L dVol\); where the volume is normalized to unity.

The localized states of this system are counted as follows. At a given intersection, a pants section is massless, and with an arbitrary D0-flux it’s energy is just the D0 brane charge. States with fixed D0-flux \(P_L\) are then obtained by partitioning that flux over \(n\) pants sections (where \(1 \leq n \geq P_L\), in the normalization where \(P_L\) is an integer.) Thus we find factorial growth of states exactly like the free field theory calculation, with \(S \approx 2\pi \sqrt{6 N_0 N_1 N_2 N_3}\). Notice that the D2 branes are in a sense auxiliary to the construction as the total D2 brane charge is zero.

4.3 Type IIB and the 3333-system

If we T-dualize the Type IIA configuration along three directions, such as \(X_1^{1,3,5}\), we find four different types of D3-branes, which now intersect at a point:

\[ Z \approx (\eta(q)\theta(q))^{4N_1 N_2 N_3}, \]

This may be obtained by taking the partition function \(Z \simeq (\eta(q)\theta(q))^{4N_1 N_2 N_3}\), for fixed \(\langle E \rangle = N_0\).
The fourth D3-brane comes from the D0-branes of the Type IIA frame. Note that each pair of these D3-branes intersects along a line, but the four branes intersect at most at a point. Thus, the low energy description would again be a $1 + 0$ quantum mechanical system.

In this U-frame, a description of the bound states appears to be very complicated. To see this consider the transformation of the string junction under the T-duality mentioned above. Depending upon which three directions that we T-dualize along, we get a pants section of D5-branes, or D3-branes, or a mixture of the two. It would seem counterintuitive to attempt an explanation of bound states of D3-branes in terms of D5-branes! However, we note that there are global conditions that must be satisfied to maintain charge conservation. These conditions (vanishing of total brane charge) imply that the description of the bound state in terms of, say, D5-branes is unstable. Perhaps there is a description of these bound states in terms of some remnant, along the lines of Refs. [16, 17].

5  M-branes on Calabi-Yau Threefolds

It is also of interest to discuss the case of M5-branes on Calabi-Yau 3-folds more directly. To begin, consider the case of $K^3 \times T^2$, with M5-branes wrapped on different complex 2-cycles. In particular, there are M5-branes wrapped on the whole $K^3$ manifold; in a Type IIB description, these branes give rise to an $A_{N_3}$ singularity times a $K3$ surface. Other M5-branes that wrap the $T^2$ as well as a 2-cycle of the $K3$ correspond to D3-branes. Again, we can go to a weakly coupled type IIB picture and repeat the steps to get the open string quiver diagram corresponding to the configuration. The twisted open strings are again the relevant degrees of freedom.

This construction can be immediately generalized to an elliptically fibered Calabi-Yau manifold $M$ with a section. Clearly, we should distinguish M5-branes which wrap a cycle on the base plus the elliptic fibre from those which wrap the base completely. The latter appear as KK monopoles while

| Brane | 0 | 10 | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 |
|-------|---|----|---|---|---|---|---|---|---|---|
| $D3_1$ | ⋄ ⋄ – ⋄ – ⋄ – ⋄ – |
| $D3_2$ | ⋄ ⋄ – – ⋄ ⋄ – – – |
| $D3_3$ | ⋄ – ⋄ ⋄ – ⋄ – – – |
| $D3_4$ | ⋄ – ⋄ – ⋄ – ⋄ – – |

11
the former become D3-branes wrapped on 2-cycles of the base, once we turn to the IIB F-theory configuration.

Therefore, we expect a local description as D3-branes wrapping cycles of the base at an orbifold singularity. The description in terms of twisted open strings should still be good locally on the D3 branes, yet the choice of which string is light changes as we move around the D3 brane, and they certainly become massless at the intersection points of these.

6 Concluding remarks

In this note, we have considered configurations of branes which form bound states at threshold. The entropy of these objects may be understood from the counting of (not necessarily perturbative) states which becomes massless when the different constituents of the black hole are brought together. The identification of these modes as string junctions is particularly appealing, as all of the degrees of freedom can be seen geometrically, but are never perturbative in this U-frame.

We have also found a perturbative picture in which the microscopic states are twisted string states on the intersection of D3-branes at an orbifold singularity. The ultraviolet theory then is a gauge theory. We have been unable, by deforming the moduli space, to find a description of the spacetime infrared conformal field theory in terms of free fields however, either on the torus, or for those Calabi-Yau manifolds for which the construction makes sense. It is expected however that this construction is capable of reproducing the chiral ring.

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