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The conformal brane-scan: an update

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Abstract: Generalizing the *The Membrane at the End of the Universe*, a 1987 paper *Supersingletons* by Blencowe and the author conjectured the existence of BPS p-brane configurations ($p = 2, 3, 4, 5$) and corresponding CFTs on the boundary of anti-de Sitter space with symmetries appearing in Nahm's classification of superconformal algebras: $\mathrm{OSp}(N|4)$ $N = 8, 4, 2, 1$; $\mathrm{SU}(2, 2|N)$ $N = 4, 2, 1$; $F^2(4)$; $\mathrm{OSp}(8^*|N)$, $N = 4, 2$. This correctly predicted the $D3$-brane with $\mathrm{SU}(2, 2|4)$ on $AdS_5 \times S^5$ and the $M5$-brane with $\mathrm{OSp}(8^*|4)$ on $AdS_7 \times S^4$, in addition to the known $M2$-brane with $\mathrm{OSp}(8|4)$ on $AdS_4 \times S^7$. However, finding non-singular AdS solutions matching the other symmetries was less straightforward. Here we perform a literature search and confirm that all of the empty slots have now been filled, thanks to a number of extra ingredients including warped products and massive Type IIA. Orbifolds, orientifolds and S-folds also play a part providing examples not predicted: $\mathrm{SU}(2, 2|3)$, $\mathrm{OSp}(3|4)$, $\mathrm{OSp}(5|4)$ and $\mathrm{OSp}(6|4)$ but not $\mathrm{OSp}(7|4)$. We also examine the status of $p = (0, 1)$ configurations.

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Our mistake is not that we take our theories too seriously,
but that we do not take them seriously enough.
Steven Weinberg

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1 Supersingletons

The *Membrane at the End of the Universe* [1–10] was the name given to a supermembrane [11] (later called the M2-brane) on the $S^1 \times S^2$ boundary of $AdS_4 \times S^7$ described by a SCFT with symmetry

$$\mathrm{OSp}(8|4) \supset \mathrm{SO}(3,2) \times \mathrm{SO}(8) \tag{1.1}$$

namely the $N = 8$ singleton supermultiplet with 8 scalar and 8 spinors and SO(8) R symmetry. We recall that representations of SO(3,2) are denoted $D(E_0, s)$ where E_0 is the lowest energy eigenvalue which occurs and s is the total angular momentum quantum number of the lowest energy state, analogous to the mass and spin of the Poincare group. However, Dirac's singletons $D(1/2, 0)$ and $D(1, 1/2)$ have no four-dimensional Poincare analogue [12] and are best interpreted a residing on the three-dimensional boundary [2, 13, 14].

Accordingly, in 1987 Blencowe and the author [3] conjectured the existence of other BPS p-brane configurations with $p = (2, 3, 4, 5)$ on the $S^1 \times S^p$ boundary of $AdS_{(p+2)}$ and corresponding CFTs with other symmetries appearing in Nahm's classification of superconformal algebras [15], listed in table 1.

In each case the boundary CFT is described by the corresponding singleton (scalar), doubleton (scalar or vector) or tripleton (scalar or tensor) supermultiplet[1] as shown in table 2. The number of dimensions transverse to the brane, $D - d$, equals the number of scalars in the supermultiplets. None of these BPS brane CFTs is self-interacting. (For non-BPS see [18, 19]).

A plot of spacetime dimension D vs worldvolume dimension $d = p + 1$, known as the *brane-scan*, is shown in table 3. This correctly predicted the $D3$-brane [20–25] with $\mathrm{SU}(\mathbf{2}, \mathbf{2}|\mathbf{4})$ on $AdS_5 \times S^5$ and the $M5$-brane [22, 23, 26] with $\mathrm{OSp}(\mathbf{8}^*|\mathbf{4})$ on $AdS_7 \times S^4$,

[1] Our nomenclature, based on the rank of AdS_{p+2}, is singleton $p = 2$, doubleton $p = (2, 3)$, tripleton $p = 5$ and differs from that of Günaydin and Minic [17].

d	G	H		Susy
6	$\mathrm{OSp}(8^*\|N)$	$\mathrm{SO}^*(8) \times \mathrm{USp}(N)$	N *even*	$8N$
5	$F^2(4)$	$\mathrm{SO}(5,2) \times \mathrm{SU}(2)$		16
4	$\mathrm{SU}(2,2\|N)$	$\mathrm{SU}(2,2) \times \mathrm{U}(N)$	$N \neq 4$	$8N$
	$\mathrm{SU}(2,2\|4)$	$\mathrm{SU}(2,2) \times \mathrm{SU}(4)$		32
3	$\mathrm{OSp}(N\|4)$	$\mathrm{SO}(N) \times \mathrm{Sp}(4,\mathbb{R})$		$4N$
2	$G_+ \times G_-$			
1	$G_\pm =$			
	$\mathrm{OSp}(N\|2)$	$\mathrm{O}(N) \times \mathrm{SU}(1,1)$		$2N$
	$\mathrm{SU}(N\|1,1)$	$\mathrm{U}(N) \times \mathrm{SU}(1,1)$	$N \neq 2$	$4N$
	$\mathrm{SU}(2\|1,1)$	$\mathrm{SU}(2) \times \mathrm{SU}(1,1)$		8
	$\mathrm{OSp}(4^*\|2N)$	$\mathrm{SU}(2) \times \mathrm{USp}(2N) \times \mathrm{SU}(1,1)$		$8N$
	$G(3)$	$G_2 \times \mathrm{SU}(1,1)$		14
	$F(4)$	$\mathrm{Spin}(7) \times \mathrm{SU}(1,1)$		16
	$D^1(2,1,\alpha)$	$\mathrm{SU}(2) \times \mathrm{SU}(2) \times \mathrm{SU}(1,1)$		8

Table 1. Following [15, 16] we list the AdS supergroups in $d \leq 6$ and their bosonic subgroups in the notation of [17].

in addition to the known $M2$-brane [11, 23] with $\mathrm{OSp}(\mathbf{8}|\mathbf{4})$ on $AdS_4 \times S^7$. The purpose of the present paper is to report that all of the other slots have now been filled, thanks to a number of extra ingredients: warped products, massive Type IIA and Chern-Simons theories. Orbifolds, orientifolds and S-folds also play a part providing examples not predicted: $\mathrm{SU}(2,2|3)$, $\mathrm{OSp}(3|4)$, $\mathrm{OSp}(5|4)$ and $\mathrm{OSp}(6|4)$ but not $\mathrm{OSp}(7|4)$. We also examine the status of $p = (0,1)$ configurations.

2 The conformal brane-scan

Comments:

- The list in table 1 is complete if one assumes that the Killing superalgebras of AdS backgrounds are simple. However a more detailed investigation reveals that there may be some additional central generators in the Killing superlgebra for AdS_3 and AdS_5 backgrounds [27, 28]

- The supersingleton lagrangian and transformation rules were also spelled out explicitly in [3]. This *conformal* or (in later terminology) *near-horizon* brane-scan differs from the scan of Green-Schwarz type kappa-symmetric branes [29] which are not in general conformal and which, in any case, include only scalar supermultiplets. Further developments and elaborations on the brane-scan are summarized in Schreiber's n-lab and references therein.

- In early 1988, Nicolai, Sezgin and Tanii [5] independently put forward the same generalization of the *Membrane at the End of the Universe* idea, spelling out the doubleton

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	Supergroup	Supermultiplet	B^-	V	χ	ϕ	D
AdS_3	$\mathrm{OSp}(n\|2)\times\mathrm{OSp}(8-n\|2)$	$(n_+,n_-)=(n,8-n), d=2$ singleton	0	0	8	8	10
	$\mathrm{OSp}(n\|2)\times\mathrm{OSp}(4-n\|2)$	$(n_+,n_-)=(n,4-n), d=2$ singleton	0	0	4	4	6
	$\mathrm{OSp}(n\|2)\times\mathrm{OSp}(2-n\|2)$	$(n_+,n_-)=(n,2-n), d=2$ singleton	0	0	2	2	4
	$\mathrm{OSp}(n\|2)\times\mathrm{OSp}(1-n\|2)$	$(n_+,n_-)=(n,1-n), d=2$ singleton	0	0	1	1	3
AdS_4	$\mathrm{OSp}(8\|4)$	$n=8, d=3$ singleton	0	0	8	8	11
	$\mathrm{OSp}(4\|4)$	$n=4, d=3$ singleton	0	0	4	4	7
	$\mathrm{OSp}(2\|4)$	$n=2, d=3$ singleton	0	0	2	2	5
	$\mathrm{OSp}(1\|4)$	$n=1, d=3$ singleton	0	0	1	1	4
AdS_5	$\mathrm{SU}(2,2\|2)$	$n=2, d=4$ doubleton	0	0	2	4	8
	$\mathrm{SU}(2,2\|1)$	$n=1, d=4$ doubleton	0	0	1	2	6
	$\mathrm{SU}(2,2\|4)$	$n=4, d=4$ doubleton	0	1	4	6	10
	$\mathrm{SU}(2,2\|2)$	$n=2, d=4$ doubleton	0	1	2	2	6
	$\mathrm{SU}(2,2\|1)$	$n=1, d=4$ doubleton	0	1	1	0	4
AdS_6	$F^2(4)$	$n=2, d=5$ doubleton	0	0	2	4	9
AdS_7	$\mathrm{OSp}(8^*\|2)$	$(n_+,n_-)=(1,0), d=6$ tripleton	0	0	1	4	10
	$\mathrm{OSp}(8^*\|4)$	$(n_+,n_-)=(2,0), d=6$ tripleton	1	0	2	5	11
	$\mathrm{OSp}(8^*\|2)$	$(n_+,n_-)=(1,0), d=6$ tripleton	1	0	1	1	7

Table 2. Superconformal groups and their singleton, doubleton and tripleton representations. B^-, V, χ, ϕ denote the number of chiral 2-forms, vector, spinors and scalars in each multiplet. The spacetime dimension D equals the worldvolume dimension d plus the number of scalars.

and tripleton lagrangian and transformation rules, in addition to the singleton. However, by insisting on only scalar supermultiplets as in [29] their list excluded the vector or tensor brane-scans of table 3. In this case, as they point out, the spheres are just the parallelizable ones S^1, S^3 and S^7.

- The two factors appearing in the $p=1$ case, $G_+\times G_-$, are simply a reflection of the ability of strings to have left and right movers on the worldsheet [30]. In this case, there are many candidate supergroups as shown in table 1, so for $p=0,1$ we did not attempt a complete list of which of these would eventually be realized. In [3], we focused on Type IIA, Type IIB and heterotic strings with $\mathrm{OSp}(n|2)_c\times\mathrm{OSp}(8-n|2)_s$, $\mathrm{OSp}(n|2)_c\times\mathrm{OSp}(8-n|2)_c$ and $\mathrm{OSp}(n|2)_c\times\mathrm{Sp}(2,\mathbb{R})$, respectively, since the singleton CFTs (but not the supergravity AdS_3 solutions) had already been identified [30]. For concreteness the Type IIA case appears on the scan of table 3.

- Even for $p\geq 2$ not all of the conformal algebras listed in table 1 appear in the scan. For example, since none of our CFTs is self-interacting, we restricted [3] $\mathrm{SU}(2,2|N)$ to $N=1,2,4$ since perturbatively $N=3$ implies $N=4$. But we now know there

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D↑								
		SCALAR						
11	.			$\mathrm{OSp}(\mathbf{8}\vert\mathbf{4})$				
10	.		$\mathrm{OSp}(n\vert 2)\times\mathrm{OSp}(8-n\vert 2)$				$\mathrm{OSp}(8^*\vert 2)$	
9	.					$F^2(4)$		
8	.				$\mathrm{SU}(2,2\vert 2)$			
7	.			$\mathrm{OSp}(4\vert 4)$				
6	.		$\mathrm{OSp}(n\vert 2)\times\mathrm{OSp}(4-n\vert 2)$		$\mathrm{SU}(2,2\vert 1)$			
5	.			$\mathrm{OSp}(2\vert 4)$				
4	.		$\mathrm{OSp}(n\vert 2)\times\mathrm{OSp}(2-n\vert 2)$	$\mathrm{OSp}(1\vert 4)$				
3	.		$\mathrm{OSp}(n\vert 2)\times\mathrm{OSp}(1-n\vert 2)$					
2	.							
1	.							
0	.	.	.	.	.	.		
		VECTOR						
11	.							
10	.				$\mathrm{SU}(\mathbf{2},\mathbf{2}\vert\mathbf{4})$			
9	.							
8	.							
7	.							
6	.				$\mathrm{SU}(2,2\vert 2)$			
5	.							
4	.				$\mathrm{SU}(2,2\vert 1)$			
3	.							
2	.							
1	.							
0	.	.	.	.	.	.	.	
		TENSOR						
11							$\mathrm{OSp}(\mathbf{8}^*\vert\mathbf{4})$	
10	.							
9	.							
8	.							
7	.						$\mathrm{OSp}(8^*\vert 2)$	
6	.							
5	.							
4	.							
3	.							
2	.							
1	.							
0	.	.	.	.	.	.	.	
	0	1	2	3	4	5	6	d→

Table 3. The brane-scans of superconformal groups: scalar supermultiplets: singletons ($p = 1, 2$), doubletons ($p = 3, 4$) and tripletons ($p = 5$); vector supermultiplets: doubletons ($p = 3$); tensor supermultiplets: tripletons ($p = 5$). The M2-, D3- and M5-branes are in boldface.

are nonperturbative interacting CFTs with just $N = 3$ [31–35]. We also focussed on $N = 1, 2, 4, 8$ in OSp$(N|4)$ since they corresponded to the division algebra $\mathbb{R}, \mathbb{C}, \mathbb{H}, \mathbb{O}$ interpretation of the four diagonal lines in the scalar branescan of table 3. The $N = 3, 5, 6, 7$ cases are discussed in section 4.

3 Significance of the brane-scan

The significance of the $M2$, $D3$ and $M5$ and indeed the other configurations on the brane-scan became clearer thanks to four major developments:

- Branes as solitons

  The realization that string theory admits p-branes as solitons [20, 21, 23, 36–41]

- M-theory

  The realization that the Type IIA superstring in $D = 10$ could be interpreted [42] as a wrapped supermembrane in $D = 11$ [11]. The membrane is a 1/2 BPS solution of $D = 11$ supergravity [43], whose spacetime approaches Minkowski space far away from the brane but $AdS_4 \times S^7$ close to the brane, jumping to the full OSp$(8|4)$ in the limit [44]. Regarded as an extremal black-brane, this limit was also called the near-horizon limit. Moreover multi-brane solutions could be obtained by stacking N branes on top of one another [43], yielding quantized 4-form flux. So $AdS_4 \times S^7$ could equally well be regarded as the large N limit. A similar story applied to its magnetic dual fivebrane [26] as a solution of $D = 11$ supergravity. Moreover, the five string theories were merely different corners of an overarching M-theory [45–47] with $D = 11$ supergravity as its low-energy limit. The membrane and fivebrane were accordingly renamed M2 and M5.

- D-branes

  The realization that p-branes carrying RR charge, with a closed-string interpretation as solitons, admitted an alternative open string interpretation as Dirichlet-branes, surfaces of dimension p on which open strings can end [25]. In particular the self-dual 3-brane, a solution of Type IIB supergravity with $AdS_5 \times S^5$ and SU$(2, 2|4)$ in the large N limit, was reinterpreted as a D3-brane and renamed accordingly.

- AdS/CFT

  The AdS/CFT conjecture [48–50] proposes 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. Another vital ingredient, missing in the early days, was the non-abelian nature of the symmetries that appear when we stack N branes on top of one another [51]. Examples include $N = 4$ Yang-Mills in $D = 4$ from $AdS_5 \times S^5$ and ABJM theory [52] from $AdS_4 \times S^7/Z_n$.

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4 The missing ingredients $p \geq 2$

Notwithstanding the success with $M2$, $D3$ and $M5$, for quite some time the status of the other slots on the brane-scans remained obscure.[2] Here we perform a literature search and confirm that all of the empty slots have now been filled, largely thanks to warped products, massive Type IIA, and Chern Simons theories as shown below

- d=6 OSp($8^*|N$) $N = 4, 2$; [54–60]
- d=5 $F^2(4)$ [59, 61–68]
- d=4 SU($2, 2|N$) $N = 4, 3, 2, 1$; [20, 31–35, 59, 69–72].
- d=3 OSp($N|4$) $N = 8, 6, 5, 4, 3, 2, 1$ [43, 52, 59, 73–80].

Comments

- We have included $N = 3$ in the $d = 4$ case and $N = 3, 5, 6$ in the $d = 3$ case, which, as previously noted, were not predicted in [3]. $N = 6$ appears in ABJM [52]. and its OSp(6|4) symmetry in [80]. A useful reference on the absence of $N = 7$ is [59].
- There are no AdS_7 solutions in Types IIA and IIB. In M all are locally isometric to $AdS_7 \times S^4$.
- There are no maximally supersymmetric AdS_6 backgrounds in M, IIA or IIB. There are no half BPS (16 supersymmetries) AdS_6 backgrounds in M and IIA with compact internal space.
- There are no such AdS_5 solutions that preserve > 16 supersymmetries in IIA and D=11 In IIB, all supersymmetric solutions are locally isometric to $AdS_5 \times S^5$. This means that all backgrounds preserving 24 supersymmetries in IIB are locally $AdS_5 \times S^5$.
- There are no > 16 AdS_4 supersymmetric solutions in IIA and IIB. In D=11 all > 16 supersymmetric solutions are locally isometric to $AdS_4 \times S^7$. This means that all solutions with 20, 24, 28 are locally $AdS_4 \times S^7$.

5 $p = 0, 1$

- d=2 [55, 78, 81–94]
- d=1 [95–106]

Comment

- Not all of the algebras in Nahm's list correspond to known solutions and indeed there may be some for which no solutions exist. A thorough and up-to-date summary maybe found in [94].

[2] In [53] we entertained the idea that they might arise from classical branes whose symmetry is enhanced when α' corrections are taken into account, but this did not pan out.

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6 Conclusion

Thus not only the M2, D3 and M5 but all of the p-brane configurations on the $S^1 \times S^p$ boundary of $AdS_{(p+1)}$ with $p = (5,4,3,2,1)$ mentioned explicitly in the 1987 paper as shown in table 3 have now been discovered: $\mathrm{OSp}(N|4)$ $N = 8,4,2,1$; $\mathrm{SU}(\mathbf{2},\mathbf{2}|\mathbf{N})$ $N = 4,2,1$; $F^2(4)$; $\mathrm{OSp}(8^*|N)$, $N = 4,2$, as have most of the $(p = 0,1)$ in Nahm's list not mentioned explicitly. Orbifolds, orientifolds and S-folds also play a part providing examples not predicted: $\mathrm{SU}(2,2|3)$, $\mathrm{OSp}(3|4)$, $\mathrm{OSp}(5|4)$ and $\mathrm{OSp}(6|4)$ but not $\mathrm{OSp}(7|4)$. To be fair, if our colleagues did not take our vector and tensor brane-scans seriously in 1987, it may be because, in the Weinberg sense, we did not take them seriously enough ourselves.

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