Anomaly-Free Brane Worlds in Seven Dimensions

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We present an orbifold compactification of the minimal seven-dimensional supergravity. The vacuum is a slice of seven-dimensional anti–de Sitter space where six-branes of opposite tension are located at the orbifold fixed points. The cancellation of gauge and gravitational anomalies restricts the gauge group and matter content on the boundaries. In addition, anomaly cancellation fixes the boundary gauge couplings in terms of the gravitational constant, and the mass parameter of the Chern-Simons term.

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The geometry of extra spacetime dimensions has recently played a prominent role in theories beyond the standard model. A generic feature of these models is that one extra dimension is compactified on a line segment (or orbifold) where boundary worlds exist at the end points. In particular, the standard model gauge and matter fields are normally assumed to be confined on the boundaries while gravity propagates in the bulk. It is this geometric separation of the two boundary worlds, interacting only gravitationally in the bulk, which has provided new insight into the hierarchy problem [1,2].

In the generic brane world scenario there is no restriction on the possible gauge group structure on the boundary. Clearly such a restriction on the gauge group of a higher-dimensional theory could help to explain the particle content of the low-energy world. The one notable example is the Horava-Witten (HW) theory in eleven dimensions [3], where the cancellation of gauge and gravitational anomalies restricts the gauge group on the ten-dimensional boundaries to be E_8. The bulk eleven-dimensional theory is then further interpreted to be the strongly coupled limit of the ten-dimensional $E_8 \times E_8$ heterotic string theory [3].

Apart from ten dimensions, gravitational anomalies also exist in six (and two) dimensions [4]. In this Letter we shall show that in seven-dimensional (7D) brane worlds the gauge group structure and matter content is similarly restricted on the six-dimensional (6D) boundaries by gauge and gravitational anomalies. Unlike the HW theory where there is a unique gauge group, we will show that many more possibilities exist in the 7D theory, which are not necessarily dimensional reductions of the HW theory. It should be stressed that, as in the HW case, supersymmetry is a central element in our construction. This is because supersymmetry dictates the possible fields allowed in the bulk as well as on the boundaries, and furthermore restricts their possible couplings.

The vacuum of the 7D theory will be a slice of AdS_7 (7D anti–de Sitter space), where six-branes of opposite tension are located at the orbifold fixed points. This leads to a localized gravity, tensor, and hypermultiplet. Moreover, anomaly cancellation will require the addition of extra vector, tensor, and hypermultiplets on the boundaries. The boundary theory must then have locally supersymmetric couplings to the 7D bulk supergravity multiplet. We will find that the gauge couplings are fixed by the anomaly cancellation in terms of the bulk gravitational coupling, and a mass parameter of the bulk Chern-Simons term.

Furthermore, by the AdS/CFT correspondence [5], our 7D bulk theory is dual to a strongly coupled 6D conformal field theory (CFT), in much the same way that the HW theory is dual to the strongly coupled $E_8 \times E_8$ heterotic string theory. This dual correspondence provides a way to further understand the properties of strongly coupled 6D conformal field theories.

Let us consider the minimal $\mathcal{N} = 2$ 7D gauged supergravity [6–8]. The gravity multiplet in this theory consists of the graviton g_{MN}, an antisymmetric three-form A_{MNK}, an SU(2) triplet of vectors A_M^{ij}, a scalar ϕ, and the SU(2) pseudo-Majorana gravitino ψ_M^i and spinor χ^i. A dual version where the three-form is replaced by a two-form is discussed in [9,10]. The capital Latin indices $M, N = 0, 1, \ldots, 6$ are 7D spacetime indices, while $i, j = 1, 2$ label the SU(2) R-symmetry group. The bosonic part of the 7D action is

$$S_{\text{bosonic}} = \frac{1}{\kappa^2}\int d^7x\sqrt{-g}\left\{\frac{1}{2}R - \frac{\sigma^{-4}}{48}F_{MNPQ}^2 - \frac{\sigma^2}{4}F_{MNi}^{j}F_j^{MNi} - \frac{1}{2}(\partial_M\phi)^2 + \frac{i}{48\sqrt{2}}F_{MNPQ}\left[F_{KLi}^{j}A_{Rj}^{i} - \frac{2ig}{3}\operatorname{tr}(A_KA_LA_R)\right]\right.$$
$$\left.\times\,\epsilon^{MNPQKLR} + 60\left(m - \frac{2}{5}h\sigma^4\right)^2 - 10\left(m + \frac{8}{5}h\sigma^4\right)^2 + \frac{h}{36}\epsilon^{KLMNPQR}F_{KLMN}A_{PQR}\right\}, \qquad (1)$$

where $m = -g\sigma^{-1}/(5\sqrt{2})$, $\sigma = \exp(-\phi/\sqrt{5})$, and g is the SU(2) gauge coupling. It can be shown that the 7D supergravity Lagrangian is invariant under $x_7 \to -x_7$ provided that [11]

$$A_{MNP} \to -A_{MNP}, \qquad A^j_{Mi} \to -A^j_{Mi},$$
$$h \to -h, \qquad m \to -m. \tag{2}$$

Since the $\mathbb{Z}_2$ transformation, $x_7 \to -x_7$ is a symmetry of the theory, we will consider the compactification down to six dimensions on the orbifold $S^1/\mathbb{Z}_2$. Then the only fields which survive at the orbifold fixed points are the $\mathbb{Z}_2$ singlets, and form the gravity $(g_{\mu\nu}, A^+_{\mu\nu}, \psi^i_\mu)$, tensor $(A^-_{\mu\nu}, \phi, \chi^i)$, and hyper (A^j_i, ξ, ψ^i) multiplets, where $A^\pm_{\mu\nu} = A^\pm_{\mu\nu 7}$, $A^j_i = A^j_{7i}$, $\xi = g_{77}$, $\psi^i = \psi^i_7$, and $\psi^i_\mu = \psi^i_{-\mu}$ are left-handed symplectic Majorana-Weyl fermions while $\chi^i = \chi^i_+$ and $\psi^i = \psi^i_+$ are right handed. Thus, the compactification of the 7D supergravity theory on an orbifold results in a chiral $\mathcal{N} = (0, 1)$ 6D theory with the above massless spectrum.

In order to make the truncated theory on the orbifold supersymmetric we must introduce six-branes at the orbifold fixed points with specific boundary potentials. This is very similar to the 5D supersymmetric Randall-Sundrum model [12,13], where supersymmetry requires the introduction of brane tensions. If we introduce the boundary potential term [11]

$$S_0 = \int d^6x \int dy \sqrt{-g}\, 20\Big(m - \frac{2}{5}h\sigma^4\Big)[\delta(y) - \delta(y - \pi R)], \tag{3}$$

then the complete action $S_7 + S_0$ will be supersymmetric, where S_7 is the full 7D action including fermionic terms, and y denotes the seventh coordinate x_7.

The supersymmetric vacuum is now the one which satisfies the Killing equations $\delta\psi_{Mi} = \delta\chi_i = 0$. Assuming that all bulk fields are zero except for the scalar field ϕ, we find that $\langle\sigma\rangle^5 = g/(8\sqrt{2}h)$. In this vacuum the bulk action becomes [11]

$$S_{\text{bulk}} = S_7 + S_{(0)} + S_{(\pi R)}, \tag{4}$$

$$S_7 = \int d^6x \int dy \sqrt{-g}\Big[\frac{1}{2}M^5 R - \Lambda_7\Big], \tag{5}$$

$$S_{(y^*)} = \int d^6x \sqrt{-g_6}[\mathcal{L}_{(y^*)} - \Lambda_{(y^*)}], \tag{6}$$

where g_6 is the induced metric on the six-brane located at y^*. The cosmological constants are given by $\Lambda_7 = -15M^5k^2$, and $\Lambda_{(0)} = -\Lambda_{(\pi R)} = 10M^5k$, where $k^5 = hg^4/16$. The Einstein equations for the combined bulk and boundary action (4) can be solved to obtain a 7D Randall-Sundrum solution

$$ds^2 = e^{-2k|y|}dx_6^2 + dy^2, \tag{7}$$

where $0 \le y \le \pi R$ and k is the AdS curvature scale. This leads to a slice of AdS_7, where the 6D gravity multiplet is localized on the UV brane at $y^* = 0$, while the tensor and hypermultiplet are localized on the IR brane at $y^* = \pi R$.

The orbifold compactification of the 7D supergravity theory has resulted in a theory with a localized gravity multiplet as well as a tensor, and a hypermultiplet. However, unlike the 5D case where arbitrary matter can be added to the boundaries [12], in the slice of AdS_7 the 6D fermions of the vector, tensor, and gravity multiplets will in general lead to gravitational and gauge anomalies.

In six dimensions the anomalies are formally described by an eight-form, I_8. For n_V vector multiplets, n_T tensor multiplets, and n_H hypermultiplets the requirement for the cancellation of the irreducible $\text{tr}R^4$ term in I_8, where R is a curvature two-form, leads to the condition $n_V - n_H - 29n_T + 273 = 0$ [14]. From the dimensional reduction of the bulk gravity multiplet there will be one tensor multiplet and one hypermultiplet in the 6D theory. However, this theory by itself is anomalous and we are forced to introduce extra boundary fields. In particular we will be interested in introducing vector multiplets on the boundary which will also produce gauge anomalies. The gauge group should be $\mathcal{G}_1 \times \mathcal{G}_2$, where each $\mathcal{G}_i$ factor is localized at the two fixed points (for simplicity we will consider only semisimple $\mathcal{G}$). Notice that although the anomaly should cancel locally, it does not have to be equally distributed between the fixed points as in the HW case.

Consider the case of $n_T = 1$. Assuming that the irreducible part of the anomaly $\text{tr}R^4$ is canceled, then the remaining reducible part (normalized as in [15]) is given by

$$I_8 = (\text{tr}R^2)^2 + \frac{1}{6}\text{tr}R^2(X_1^{(2)} + X_2^{(2)}) - \frac{2}{3}(X_1^{(4)} + X_2^{(4)}), \tag{8}$$

where $X_i^{(n)} = \text{Tr}F_i^n + \sum_i n_i \text{tr}_i F_i^n$, and Tr, tr_i are traces in the adjoint and the R_i representation, respectively, whereas n_i is the number of hypermultiplets in the representation R_i. The anomaly (8) can be canceled by the Green-Schwarz mechanism [16] provided that it can be factorized into the form

$$I_8 = \Big(\text{tr}R^2 + u_i \sum_i \text{tr}F_i^2\Big)\Big(\text{tr}R^2 + v_i \sum_i \text{tr}F_i^2\Big), \tag{9}$$

where u_i, v_i are constants. This ensures that at the massless level the theory is anomaly free.

However, from the 7D orbifold perspective the 6D anomaly must be distributed between the two fixed points. The bulk topological Chern-Simons term plays a crucial role in canceling the anomaly by a local Green-Schwarz mechanism as occurs in the 11D HW theory. Thus, by writing $I_8 = I_8^{(1)} + I_8^{(2)}$ and demanding the local factorization

$$I_8^{(i)} = (c_i \text{tr}R^2 + a_i \text{tr}F_i^2)(\text{tr}R^2 + b_i \text{tr}F_i^2), \tag{10}$$

where a_i, b_i, c_i are constants and $c_1 + c_2 = 1$, the two terms in the sum I_8 vanish by a local Green-Schwarz mechanism at each orbifold fixed point [17]. It can be shown [11] that the factorization (10) is indeed possible as long as $\alpha_i \mathrm{tr} F_i^4 = 0$. For $\alpha_i \neq 0$, this occurs for all the irreps of E_8, E_7, E_6, F_4, G_2, SU(3), SU(2), U(1), for the 28 of Sp(4) and SU(8), and all the irreps of SO(2n) with highest weight $(f_1, f_2, f_1, -f_2, 0, ..., 0)$ in the Gel'fand-Zetlin basis [18].

In the case where there is only one tensor multiplet in the 6D theory ($n_T = 1$), arising from the dimensional reduction of the bulk theory, we are lead to the irreducible constraint $n_H = n_V + 244$. Under $\mathcal{G}_1 \times \mathcal{G}_2$ let us suppose that the total number of hypermultiplets consists of the representations $n_1(d_{F_1}, 1) + n_2(1, d_{F_2}) + (n_S + 1) \times (1, 1)$, where d_{F_i} is the dimension of the fundamental representation of the group $\mathcal{G}_i$, and $n_{1,2}, n_S$ are the numbers of each representation. Note that we have automatically included the extra singlet hypermultiplet (or radion multiplet) arising from the dimensionally reduced bulk theory. Thus, assuming the irreducible constraint is satisfied together with (9) and (10), we find the following solutions for $\mathcal{G}_1 = \mathcal{G}_2 = \mathcal{G}$:

$\mathcal{G} \times \mathcal{G}$	$n_1 + n_2$	n_S
$G_2 \times G_2$	20	131
$F_4 \times F_4$	10	87
$E_6 \times E_6$	12	75
$E_7 \times E_7$	8	61

In particular, we see that not only the gauge groups, but also the number of hypermultiplet generations, are restricted on the boundaries. For example in the $E_6 \times E_6$ case, if one boundary contains 3 generations of the fundamental 27 then the other boundary must have 9 generations. There is also an (n_1, n_2, n_S) solution (2, 7, 156), and similar exceptions exist for the other gauge groups. It is also possible to have two different gauge groups distributed between the fixed points. These include $E_8 \times E_7, E_8 \times E_6, E_8 \times F_4, E_8 \times G_2, E_7 \times E_6, E_7 \times F_4, E_7 \times G_2, E_6 \times F_4, E_6 \times G_2$, and $F_4 \times G_2$. These exceptions and other possibilities will be presented in Ref. [11]. Our solutions differ from the usual compactifications of the HW theory because in HW compactifications there is matter charged under both local gauge groups [19,20]. This is true even in compactifications of weakly coupled string theory [21].

Note also that in the $n_T = 1$ case, there are no solutions with SU(n), SO(n), or Sp(n) gauge groups because the cancellation of the quartic Casimir does not allow one to simultaneously satisfy (9) and (10). Nevertheless, as will be shown in [11] such solutions can exist for $n_T > 1$. However, in this case one must employ the generalized Green-Schwarz mechanism of Ref. [22].

Finally, note that the 6D theory may still be ill defined due to nonperturbative anomalies [18,23,24]. Global anomalies exist as long as $\pi_6(\mathcal{G})$ is nontrivial. In our case only the gauge group G_2 may be plagued by global anomalies since $\pi_6(G_2) = \mathbb{Z}_3$. In particular, with n_F fundamentals of G_2, the condition for the absence of global anomalies is $n_F = 1 \bmod 3$ [25]. Thus, for the $G_2 \times G_2$ case, the absence of nonperturbative anomalies further restricts the values of (n_1, n_2) in the above table.

The addition of vector, tensor, and hypermultiplets propagating on the boundaries implies that there must exist locally supersymmetric couplings of the 6D multiplets to the 7D supergravity multiplet propagating in the bulk. Let us consider first the addition of vector multiplets on the boundary. One can show [11] that the combined bulk and boundary action is locally supersymmetric up to fermionic bilinear terms where

$$S_{YM} = -\frac{1}{\lambda^2}\int d^6x\sqrt{-g}\Bigg[\frac{\sigma^{-2}}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{1}{2}\bar{\lambda}^a\Gamma^\mu D_\mu\lambda^a + \frac{\sigma^{-1}}{4}\bar{\psi}_\mu\Gamma^{\nu\rho}\Gamma^\mu\lambda^a F^a_{\nu\rho} + \frac{\sigma^{-1}}{2\sqrt{5}}\bar{\lambda}^a F^a_{\mu\nu}\Gamma^{\mu\nu}\chi - \frac{\sigma^{-2}}{24\sqrt{2}}\bar{\lambda}^a\Gamma^{\mu\nu\rho}\lambda^a F_{\mu\nu\rho 7} + \frac{i\sigma}{2\sqrt{2}}\bar{\lambda}^{ai}\Gamma^\mu F^j_{\mu 7 i}\lambda^a_j\Bigg], \tag{11}$$

and the supersymmetry transformations are

$$\delta A^a_\mu = \frac{1}{2}\sigma\bar{\epsilon}\Gamma_\mu\lambda^a, \tag{12}$$

$$\delta\lambda^a = -\frac{1}{4}\sigma^{-1}\Gamma^{\mu\nu}F^a_{\mu\nu}\epsilon. \tag{13}$$

As in the HW theory one requires the modification of the Bianchi identity for $F_{\mu\nu\rho 7}$. The modified Bianchi identity has the effect of changing the Chern-Simons term in S_{bulk} into a Green-Schwarz term. The Green-Schwarz term precisely cancels the anomalous variation of the effective action for 6D Weyl fermions provided that the boundary gauge coupling λ satisfies $\lambda^2 = 8\kappa\sqrt{3\pi^3 h/\gamma}$, where γ is a constant defined by $X_i^{(4)} = \gamma(\mathrm{tr}F^2)^2$. This relation is similar to that found in the HW theory, except that now there is an extra dependence on the topological mass parameter, h.

Similarly we can introduce hypermultiplets on the boundary. Under the supersymmetry transformations

$$\delta\varphi^\alpha = \frac{1}{2}\sigma^{-1/2}V^\alpha_{iY}\bar{\epsilon}^i\zeta^Y, \tag{14}$$

$$\delta\zeta^Y = \frac{1}{2}\sigma^{1/2}V^Y_{\alpha i}\Gamma^\mu\partial_\mu\varphi^\alpha\epsilon^i, \tag{15}$$

the locally supersymmetric boundary action for neutral hypermultiplets is [11]

$$S_H = \int d^6x\sqrt{-g}\bigg[-\frac{1}{2}\, g_{\alpha\beta}(\varphi)\partial_\mu\varphi^\alpha\partial^\mu\varphi^\beta - \frac{1}{2}\bar{\zeta}^Y\Gamma^\mu D_\mu\zeta_Y + \frac{\sigma^{1/2}}{2\sqrt{5}} V_{\alpha iY}\bar{\zeta}^Y\Gamma^\mu\partial_\mu\varphi^\alpha\chi^i + \frac{\sigma^{1/2}}{2}\bar{\psi}^i_\mu\Gamma^\nu\Gamma^\mu\partial_\nu\varphi^\alpha V^Y_{\alpha i}\zeta_Y + \frac{\sigma^{1/2}}{24\sqrt{2}}\bar{\zeta}^Y\Gamma^{\mu\nu\rho}\zeta_Y F_{7\mu\nu\rho}\bigg], \tag{16}$$

where $\varphi^\alpha(\alpha, \beta = 1, \ldots, 4n_H)$ and $\zeta^Y(X, Y = 1, \ldots, 2n_H)$ are the scalars and fermions of the n_H hypermultiplets, respectively, and $g_{\alpha\beta}$ is the metric of the scalar manifolds. Similarly, as in the case of the vector multiplets the Bianchi identity for $F_{7\mu\nu ij}$ must be modified which results in a correction to the supersymmetry transformation of $F^i_{\mu 7j}$. This is crucial in showing that the scalar manifold is quaternionic, as required by 6D $\mathcal{N} = (0, 1)$ local supersymmetry [26]. Details will be presented elsewhere [11].

In summary, we have presented a new class of models with a boundary, where the gauge group structure on the boundary is determined by the cancellation of gauge and gravitational anomalies. The vacuum of the bulk theory is a slice of AdS_7 with localized gravity. Anomaly cancellation also places constraints on the possible boundary matter, and determines the boundary gauge coupling in terms of the bulk gravitational constant, and the mass parameter of the Chern-Simons term. By the AdS/CFT correspondence our 7D brane world is dual to a 6D CFT. Much like the 5D counterpart [27], this CFT is defined with a cutoff, and couples to gravity. Boundary fields on the UV (IR) brane are identified as fundamental (composite) states in the CFT, and the strong coupling regime of this 6D theory is described by our 7D solution.

The 6D boundary theories also have phenomenological interest. For example, the hierarchy problem is naturally solved and the gauge group structure on the boundaries can contain the standard model gauge group. Moreover, there are also possible monopole compactifications on S^2, such as those considered in [29], which give rise to chiral four-dimensional $\mathcal{N} = 1$ theories. The low energy particle content would then be fixed by anomaly cancellation (see also [30]), and the hierarchy problem is explained by the warped bulk. These issues as well as cosmological implications remain to be investigated.

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