

# Deconstruction, $G_2$ Holonomy, and Doublet-Triplet Splitting

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We describe a mechanism for using discrete symmetries to solve the doublet-triplet splitting problem of four dimensional supersymmetric GUT's. We present two versions of the mechanism, one via “deconstruction,” and one in terms of  $M$ -theory compactification to four dimensions on a manifold of  $G_2$  holonomy.

## 1. Introduction

One of the central problems in four-dimensional Grand Unified Theories (GUT's) is the splitting between standard model Higgs doublets and their color triplet partners. The problem persists in supersymmetric GUT's, which will be the focus of the present paper.

In  $SU(5)$  models, for example, the Higgs doublets can be naturally placed in chiral superfields  $V, \tilde{V}$  transforming as  $\mathbf{5} \oplus \bar{\mathbf{5}}$ .  $V$  has for its standard model content a possible Higgs doublet  $H$  as well as a color triplet  $Q$ , while  $\tilde{V}$  has fields  $\tilde{H}, \tilde{Q}$  transforming in the conjugate representations. To get standard model phenomenology,  $H$  and  $\tilde{H}$  must be essentially massless at the GUT scale – receiving mass only at the electroweak scale. But  $Q$  and  $\tilde{Q}$  have renormalizable couplings – related by  $SU(5)$  to the couplings of  $H$  and  $\tilde{H}$  that are needed to give mass to quarks and leptons – that mediate baryon number violating processes.  $Q$  and  $\tilde{Q}$  must therefore obtain masses close to the GUT scale in order to obtain an even roughly reasonable proton lifetime. (Even if this is achieved, there are more obstacles to getting a realistic proton lifetime; they will be discussed in section 2.1.)

A variety of field theory solutions to the doublet-triplet splitting problem or fine-tuning problem have been proposed. For a brief review of some of the proposals up to 1995, see [1]. There also are more recent field theoretic proposals such as one based on strong supersymmetric dynamics [2].

Possible solutions to the problem also exist in the framework of string theory and higher dimensions [3]. In this context, unification only arises in some dimension greater than four and the unified group  $G$  is broken down to the standard model (or an extension of the standard model that is phenomenologically viable at relatively low energies) in the process of compactification. A key ingredient in this approach is “gauge symmetry breaking by Wilson lines,” in which one aims, while compactifying from ten to four dimensions, to project the dangerous color triplets out of the low energy spectrum while leaving the Higgs doublets.<sup>1</sup> For a review of Calabi-Yau compactification of the heterotic string, in which this mechanism can naturally be incorporated, see chapters 14-16 of [5]. For a more recent discussion of some stringy constructions, see [6]. Mechanisms of roughly this type have

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<sup>1</sup> A generalization of symmetry breaking by Wilson lines is symmetry breaking by orbifolds [4], where the symmetry breaking is carried out using a discrete symmetry that does not act freely. In perturbative string theory, this is not usually used as a mechanism for GUT symmetry breaking, because typically the massless twisted sector modes would not be in complete  $G$  multiplets and the successes of grand unification would not be preserved.

lately come to be widely studied from a more phenomenological and bottom-up point of view [7-11].

In the present paper, we will be concerned with solutions to the fine-tuning problem that make use of discrete symmetries. In fact, some but not all field theory proposals for the fine-tuning problem and some but not all string theory proposals make use of discrete symmetries.<sup>2</sup> The basic reason that discrete symmetries might be relevant to the fine-tuning problem, in a supersymmetric GUT-like theory, is as follows.

Suppose that we are given a discrete symmetry  $F$  under which the components  $(Q, H)$  of the  $\mathbf{5}$  transform as  $(e^{i\alpha}, e^{i\beta})$ , while the components  $(\tilde{Q}, \tilde{H})$  of the  $\bar{\mathbf{5}}$  transform as  $(e^{i\gamma}, e^{i\delta})$ . If  $e^{i(\alpha+\gamma)} = 1$ , then this symmetry allows  $Q$  and  $\tilde{Q}$  to get GUT scale masses, while if  $e^{i(\beta+\delta)} \neq 1$ , then  $H$  and  $\tilde{H}$  are massless. In fact, in this scenario, the “ $\mu$ -term,” an  $H\tilde{H}$  term in the superpotential that is needed for supersymmetric phenomenology, violates  $F$  and can only arise at lower energies where (hopefully)  $F$  is spontaneously broken.

From a field theory point of view, it can be difficult, depending on one’s assumptions, to get a discrete symmetry with the necessary properties. It is generally not true in GUT’s that a discrete symmetry of the low energy theory must commute with the GUT group  $G$ ; it might be the product of a discrete symmetry that “normalizes” the standard model subgroup of  $G$  (conjugates it to itself) times an ordinary discrete symmetry that commutes with  $G$ . However, if  $G = SU(5)$ , an element of  $G$  that normalizes  $SU(3) \times SU(2) \times U(1)$  is actually contained in  $SU(3) \times SU(2) \times U(1)$ . This means that, modulo a standard model gauge transformation, a discrete symmetry in a four-dimensional  $SU(5)$  model actually commutes with  $SU(5)$ . A discrete symmetry that is the product of a standard model gauge transformation and a symmetry that commutes with  $SU(5)$  leaves the  $H\tilde{H}$  term in the superpotential invariant if and only if the  $Q\tilde{Q}$  term is invariant. (Both terms are invariant under the standard model gauge group, and a discrete symmetry that commutes with  $SU(5)$  does not distinguish them either.) So such a discrete symmetry cannot solve the fine-tuning problem.

Things are no different in four-dimensional GUT’s based on the other standard simple GUT groups such as  $SO(10)$  and  $E_6$ . The reason is that each of these groups, with the usual standard model embedding, contains a unique  $SU(5)$  subgroup  $G'$  that contains  $SU(3) \times SU(2) \times U(1)$ , and the above argument can be carried out using  $G'$ .

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<sup>2</sup> Discrete symmetries were not used, for example, in the doublet-triplet splitting mechanism proposed in [3].

As explained in [12], in the context of a four-dimensional  $SU(5)$  model, mixing the  $\mathbf{5}$  and  $\bar{\mathbf{5}}$  with additional  $SU(5)$  representations does not change this conclusion, but if one starts above four dimensions, one can readily get discrete symmetries of the desired kind.

This is a benefit of having extra dimensions. However, it has recently been pointed out [13,14] that some higher-dimensional setups can be “deconstructed,” or simulated by a four-dimensional model in which, roughly speaking, the extra dimensions are replaced by a lattice (which may have a very small number of lattice points). In section 2, following this lead, we deconstruct one version of the higher-dimensional approach to the doublet-triplet splitting problem. In its minimal form, this involves beginning with an  $SU(5) \times SU(5)$  gauge theory, with the standard model diagonally embedded in the product of the two  $SU(5)$ ’s. Such structures have been considered in many papers on deconstruction such as [13,15]. By starting with  $SU(5) \times SU(5)$  rather than  $SU(5)$ , the constraints on discrete symmetries are relaxed, and it is readily possible to find discrete symmetries that can solve the fine-tuning problem.

In section 3, we present a higher-dimensional version of the same mechanism. In fact, we describe how discrete symmetries that can naturally split triplets from doublets can arise in the context of  $M$ -theory compactification to four dimensions on a manifold of  $G_2$  holonomy. This is a natural way to obtain a four-dimensional model with  $\mathcal{N} = 1$  supersymmetry, and since it can be dual to heterotic string compactification on a Calabi-Yau threefold, it is fairly clear that it must be possible to express some of the mechanisms for doublet-triplet splitting that are familiar for the heterotic string in the language of compactification on  $G_2$  manifolds. We do this in section 3. Some of the ingredients of this construction have appeared in previous papers [16,17].

In fact, the approach sketched in section 3 was worked out first. Deconstruction was attempted following a question raised by Hsin-Chia Cheng, when this work was presented in a seminar at the University of Chicago.

### *Similarities And Differences Of The Two Approaches*

The deconstructed theory presented in section 2 is not technically a unified theory by some definitions, since the  $SU(5) \times SU(5)$  gauge theory has two independent gauge couplings (there is no symmetry exchanging the two factors). However, the diagonal embedding of the standard model ensures that most of the familiar consequences of grand unification, such as the SUSY-GUT prediction for  $\sin^2 \theta_W$  and constraints on the quantum

numbers of quarks and leptons, do hold. By contrast, the  $M$ -theory model unifies not just the gauge fields but also the Higgs fields, standard model fermions, and gravity.

The two types of model differ in a few other interesting ways. In  $M$ -theory models, it is believed (there is not a complete proof of this) that the discrete symmetries are always anomaly-free (they may be spontaneously broken by the transformation law of an axion). In the context of deconstruction, opinions may differ about whether an anomalous discrete symmetry should be considered technically natural, but at any rate it would be phenomenologically viable to try to solve the fine-tuning problem using such a symmetry.

In the deconstructed model, gauge anomalies must cancel separately in each  $SU(5)$  factor of the gauge group. Gauge anomaly cancellation is a less severe constraint in the  $M$ -theory approach, since there is an anomaly inflow mechanism [16] (analogous to anomaly inflow for  $D$ -branes [18]) that can shift the anomaly from one factor to the other. Anomaly inflow, since it involves Chern-Simons-like couplings, appears difficult to deconstruct, but see [19] (which appeared on hep-ph a few days after the original version of the present paper). Finally, like most perturbative heterotic string models [20], the models derived from  $M$ -theory generally have superheavy unconfined color singlet particles with fractional electric charges, and reciprocally a larger quantum of magnetic charge than would be expected in a four-dimensional GUT. The deconstructed models obey conventional quantization of electric and magnetic charge.

After submission of the original version of the present paper, I learned of [21], which presents a construction similar to that in section 2.1.

## 2. $SU(5)' \times SU(5)''$ And Deconstruction

### 2.1. Direct Construction Of The Model

We start with a gauge theory in four-dimensions in which the gauge group is the product  $G = SU(5)' \times SU(5)''$  of two copies of  $SU(5)$ . We suppose that the standard model group is diagonally embedded in the product of the two factors. The hypercharge group  $U(1)_Y$ , for example, is the diagonal subgroup of  $U(1)'_Y \times U(1)''_Y$ , the product of the hypercharge groups of the two  $SU(5)$ 's.

We assume that, in addition to the standard model being unbroken, a discrete global symmetry group  $F' \cong \mathbf{Z}_n$  is unbroken at the GUT scale. We take  $F'$  to be a diagonal product of an ordinary global symmetry  $F = \mathbf{Z}_n$  (which commutes with  $G$ ) and the  $\mathbf{Z}_n$  subgroup of  $U(1)''_Y$ . In what follows, we pick a fixed generator of  $F'$ . An explicit and fairly

simple set of Higgs fields that can break  $G \times F$  to  $SU(3) \times SU(2) \times U(1) \times F'$  will be given in section 2.2.

Given this low energy structure, it is straightforward to solve the doublet-triplet splitting problem. We suppose that the Higgs bosons, whose expectation values will ultimately give masses to quarks and leptons, consist of multiplets  $V, \tilde{V}$  transforming under  $SU(5)' \times SU(5)''$  as  $(\mathbf{5}, \mathbf{1}) \oplus (\mathbf{1}, \bar{\mathbf{5}})$ .  $V$  decomposes under the standard model as  $(Q, H)$  and  $\tilde{V}$  decomposes as  $(\tilde{Q}, \tilde{H})$ ; here (as in the introduction)  $H$  and  $\tilde{H}$  are standard model Higgs fields and  $Q, \tilde{Q}$  are colored partners.

$V$  is neutral under  $U(1)''_Y$ , so in this multiplet  $F'$  acts as an ordinary global symmetry. Hence, under the generator of  $F'$ ,  $V$  transforms as

$$\begin{pmatrix} Q \\ H \end{pmatrix} \rightarrow e^{i\alpha} \begin{pmatrix} Q \\ H \end{pmatrix}, \quad (2.1)$$

for some  $\alpha$ . But on the  $(\mathbf{1}, \bar{\mathbf{5}})$ ,  $F'$  acts as the product of a global symmetry and a  $U(1)''_Y$  gauge transformation, so the transformation under the generator of  $F'$  is

$$\begin{pmatrix} \tilde{Q} \\ \tilde{H} \end{pmatrix} \rightarrow \begin{pmatrix} e^{i\gamma} \tilde{Q} \\ e^{i\delta} \tilde{H} \end{pmatrix}. \quad (2.2)$$

Here  $e^{i\gamma}$  and  $e^{i\delta}$  are arbitrary  $n^{\text{th}}$  roots of 1, depending on the choice of  $F$  charge of the  $(\mathbf{1}, \bar{\mathbf{5}})$  as well as the precise diagonal subgroup of  $F \times U(1)''_Y$  we have chosen for  $F'$ . Now it is clear how to solve the doublet-triplet splitting problem; we merely choose the charges so that  $e^{i(\alpha+\gamma)} = 1$  but  $e^{i(\alpha+\delta)} \neq 1$ . Then a  $Q\tilde{Q}$  term in the superpotential is  $F'$ -invariant, but  $F'$  forbids an  $H\tilde{H}$  term.

Now let us consider how to incorporate quarks and leptons in this model. There are many choices, as the standard model quantum numbers of quarks and leptons could originate from either or both of the two  $SU(5)$ 's. We consider two illustrative models:

#### *All Quarks And Leptons From The First Factor*

In our first model, we assume that all quark and lepton quantum numbers arise from the first  $SU(5)$ . So the quarks and leptons arise from three copies of  $(\mathbf{10}, \mathbf{1}) \oplus (\bar{\mathbf{5}}, \mathbf{1})$ .  $F'$  acts by ordinary  $G$ -invariant global symmetries on these multiplets. We assume that the  $(\mathbf{10}, \mathbf{1})$ 's all transform by multiplication by  $e^{i\sigma}$ , with a common  $\sigma$ , and likewise the  $(\bar{\mathbf{5}}, \mathbf{1})$ 's all transform by multiplication by  $e^{i\tau}$  for some  $\tau$ .

Let us see what constraints are required by phenomenology. To give masses to up quarks, we want  $H(\mathbf{10}, \mathbf{1})^2$  superpotential couplings; for this, we need

$$e^{i(\alpha+2\sigma)} = 1. \quad (2.3)$$

To give masses to down quarks and charged leptons, we want  $\tilde{H}(\mathbf{10}, \mathbf{1})(\mathbf{1}, \bar{\mathbf{5}})$  interactions; for this, we need

$$e^{i(\delta+\sigma+\tau)} = 1. \quad (2.4)$$

The experimental observation of neutrino masses strongly suggests that an  $H^2(\bar{\mathbf{5}}, \mathbf{1})^2$  coupling is allowed; in the context of GUT's, this leads to neutrino masses of roughly the observed magnitude. For this coupling to be allowed, we need

$$e^{2i(\alpha+\tau)} = 1. \quad (2.5)$$

But we do not want to allow a  $H(\bar{\mathbf{5}}, \mathbf{1})$  mass term, so we want

$$e^{i(\alpha+\tau)} = -1. \quad (2.6)$$

We can solve these equations in terms of an arbitrary angle  $\sigma$ :<sup>3</sup>

$$\begin{aligned} \alpha &= -2\sigma \\ \tau &= 2\sigma + \pi \\ \delta &= -3\sigma + \pi. \end{aligned} \quad (2.7)$$

Finally, and of great importance, to get a realistic proton lifetime, we need additional restrictions. We want to avoid renormalizable couplings  $(\mathbf{10}, \mathbf{1})(\bar{\mathbf{5}}, \mathbf{1})^2$  that violate baryon number, so we want  $e^{i(\sigma+2\tau)} \neq 1$ , or in terms of the above solution

$$5\sigma \neq 0. \quad (2.8)$$

Moreover, it is highly desirable to avoid  $(\mathbf{10}, \mathbf{1})^3(\bar{\mathbf{5}}, \mathbf{1})$  terms in the superpotential, which lead to dimension five baryon nonconserving operators. It is difficult for a GUT-like model to generate such terms and have a sufficiently long-lived proton; for a recent account, see [22]. So we want  $e^{i(3\sigma+\tau)} \neq 1$ , or in terms of the above solution,

$$5\sigma + \pi \neq 0. \quad (2.9)$$

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<sup>3</sup> All equations for these angles are of course understood mod  $2\pi$ .

One interesting feature of this model is that although the  $H(\mathbf{10}, \mathbf{1})^2$  Yukawa couplings that give masses to up quarks can arise from ordinary  $G$ -invariant cubic terms  $V(\mathbf{10}, \mathbf{1})^2$  in the superpotential, the  $\tilde{H}(\mathbf{10}, \mathbf{1})(\bar{\mathbf{5}}, \mathbf{1})$  couplings that give the down quarks and charged lepton masses cannot so arise, given that  $\tilde{H}$  transforms as  $(\mathbf{1}, \bar{\mathbf{5}})$ . These latter couplings must instead be induced from unrenormalizable superpotential couplings of the general form  $\tilde{V}(\mathbf{10}, \mathbf{1})(\bar{\mathbf{5}}, \mathbf{1})\Phi$ , where  $\Phi$  is constructed from fields (introduced in section 2.2) whose expectation values break  $G \times F$  to the low energy subgroup  $SU(3) \times SU(2) \times U(1) \times F'$ , which does allow the  $\tilde{H}(\mathbf{10}, \mathbf{1})(\bar{\mathbf{5}}, \mathbf{1})$  couplings. Because they arise from unrenormalizable couplings, it is natural to expect the down quark and charged lepton masses to be less than the up quark masses. For the third generation, this is true, as the bottom quark and tau lepton are much lighter than the top quark. If the ratios  $m_b/m_t$  and  $m_\tau/m_t$  are really to be obtained this way, the cutoff scale characterizing unrenormalizable interactions cannot be too much bigger than the GUT scale, since after all  $m_b/m_t$  and  $m_\tau/m_t$  are only moderately small. Moreover, the fact that the first two generations are so light compared to the top quark would presumably require some further mechanism.

Finally, the spectrum of the model as we have presented it so far cannot be the whole story, since it is anomalous. The only chiral multiplet so far introduced that carries  $SU(5)''$  charges is the Higgs multiplet  $\tilde{V}$ , transforming as  $(\mathbf{1}, \bar{\mathbf{5}})$ . The couplings of this field are anomalous. Likewise,  $SU(5)'$  couples to three anomaly-free copies of  $(\mathbf{10}, \mathbf{1}) \oplus (\bar{\mathbf{5}}, \mathbf{1})$  as well as a Higgs multiplet  $V$  transforming as  $(\mathbf{5}, \mathbf{1})$ ; its couplings are again anomalous. A simple way to cancel the anomalies is to add additional fields  $\tilde{S}, S$  transforming as  $(\bar{\mathbf{5}}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{5})$ ; their  $F$  quantum numbers should be restricted to avoid various undesirable couplings. If one believes that  $F$  should be anomaly-free for naturalness of the model, then the  $F$  quantum numbers of  $\tilde{S}, S$  must be further constrained. Purely for phenomenological purposes, however, gauge anomalies in  $F$  would not lead to trouble.

It is interesting to speculate that the fields  $\tilde{S}, S$  might play the role of “messenger fields” in gauge-mediated supersymmetry breaking (for surveys see [23,24]), communicating to the standard model fields the occurrence of supersymmetry breaking in a hidden sector. For this, there might be singlets  $T$  whose expectation values violate supersymmetry and  $F'$  and which have superpotential couplings  $TS\tilde{S}$ . Actually, since the color singlet and color triplet components of  $S$  transform differently under  $F'$  (and there is no such splitting for  $\tilde{S}$ ), one would need different  $T$  fields transforming differently under  $F'$  to couple to the color singlets and triplets in  $S\tilde{S}$ .



### *Mixed Origin Of Quarks And Leptons*

For a second model, which we will not develop as fully, we consider one possibility among many to use the distinct gauge theoretic origin of the two different Higgs fields to constrain quark and lepton masses. Since the top quark is much heavier than the charm or up quark, we might assume that the top originates from a  $(\mathbf{10}, \mathbf{1})$  while the charm and up quarks originate from two copies of  $(\mathbf{1}, \mathbf{10})$ . Then the top quark gets a mass from renormalizable  $V(\mathbf{10}, \mathbf{1})^2$  couplings, while the charm and up masses originate from unrenormalizable interactions. Since the bottom quark and tau lepton are much heavier than the analogous particles in the first two generations, one might similarly suppose that the bottom quark arises from a  $(\mathbf{1}, \bar{\mathbf{5}})$  (so that it can get its bare mass from a renormalizable coupling  $\tilde{V}(\mathbf{1}, \mathbf{10})(\mathbf{1}, \bar{\mathbf{5}})$ ) and the others from two copies of  $(\bar{\mathbf{5}}, \mathbf{1})$ . This spectrum, including the Higgs fields, is fortuitously anomaly-free so we do not need additional fields analogous to  $S, \tilde{S}$  of the first model.

A problem with this model is that it will be hard to generate masses for all down quarks and charged leptons. In fact, one down quark mass and one charged lepton mass would have to come from a coupling  $\tilde{H}(\bar{\mathbf{5}}, \mathbf{1})(\mathbf{1}, \mathbf{10})$ . Because different components of the  $(\mathbf{1}, \mathbf{10})$  transform differently under  $F'$ , while there is no such splitting for the  $(\bar{\mathbf{5}}, \mathbf{1})$ , this coupling cannot give a mass to both a down quark and a charged lepton, no matter what  $F'$  charges we assume.

### *2.2. Interpretation Via Deconstruction*

Next we will explain in what sense the above model can arise via deconstruction. First, let us explain what manifold is being deconstructed. We let  $D_0$  be a two-dimensional disc. We can triangulate it as in the figure, with one vertex  $P$  in the center and  $n$  vertices  $Q_1, \dots, Q_n$  on the boundary.

The space we want to deconstruct is not  $D_0$ , but rather a space  $D$  obtained by imposing the following equivalence relation: two points in  $D_0$  that are *on the boundary* are equivalent if they differ by a  $2\pi/n$  rotation of the boundary. Thus, an equivalence relation is imposed only on the boundary. If  $n = 2$ ,  $D$  is an unorientable manifold, the real projective plane  $\mathbf{RP}^2$ . Its deconstruction was described in [25] in the discussion of “spider web theory space.” The case  $n = 2$  would not quite work for us, at least in the first model presented above, because (2.9) and (2.8) could not be obeyed. The deconstruction, however, is similar for  $n > 2$ , though  $D$  is not a manifold (but a singular topological space) for  $n > 2$ . In fact, the triangulation or deconstruction of  $D$  is very simple. There are only

two vertices,  $P$  and  $Q_1$  (since the equivalence relation identifies all the  $Q_i$ ), connected by the edges shown in the figure.

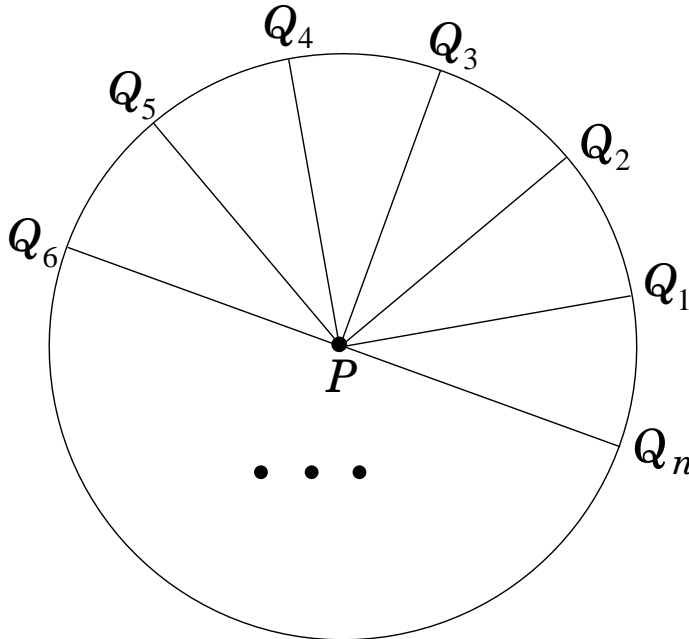


Figure 1: Moose or quiver diagram representing the triangulation or deconstruction of a two-dimensional disc  $D_0$ .

Suppose that we want to do lattice gauge theory of gauge group  $G$  on  $D$ , understood in terms of this triangulation. The lattice gauge field that lives on the link in figure 1 from  $Q_i$  to  $Q_{i+1}$  is a group element  $W$ ; because of the equivalence relation,  $W$  is independent of  $i$ . Similarly, on the link from  $P$  to  $W_i$ , the lattice gauge field is a group element  $U_i$ . To minimize the energy, we want the holonomy around each two-dimensional plaquette to equal 1. For the triangulation in the figure, this means that for each  $i$  we need

$$U_i W U_{i+1}^{-1} = 1. \quad (2.10)$$

Taking the product of these relations for  $i = 1, \dots, n$ , we deduce that  $W^n = 1$ . It is possible (by making a gauge transformation at  $P$ ) to pick  $U_1 = 1$ , and then (2.10) determines the other  $U_i$ . So the  $G$ -symmetry breaking is determined entirely by the choice of  $W$ . This result really reflects the fact that a lattice gauge field with trivial holonomy around every plaquette gives a representation of the fundamental group, which for  $D$  is  $\mathbf{Z}_n$ . Finiteness of the fundamental group results means that symmetry breaking by Wilson lines depends on discrete choices [3,25], in this case the choice up to conjugacy of  $W \in G$  with  $W^n = 1$ .

We interpret  $F \cong \mathbf{Z}_n$  as the discrete symmetry that rotates the disc in figure (1) by an angle  $2\pi/n$ . Note that  $F$  is a non-trivial symmetry of  $D$ .  $F$  might sound suspiciously similar to the equivalence relation that was imposed on  $D_0$  to get  $D$ . The difference is that the equivalence relation was imposed only on the boundary of  $D_0$ , while  $F$  acts on all of  $D$ . So  $F$  acts non-trivially on  $D$ , leaving fixed the point  $P$  and also the boundary, where  $F$  generates the equivalence relation.

Now, let us ask if the choice of a gauge field obeying (2.10) leaves  $F$  unbroken. In fact, it does. Even in the presence of the gauge fields,  $F$  is unbroken if accompanied by the gauge transformation  $W$  at the site  $Q_1$  (and no gauge transformation at  $P$ ). Under such a gauge transformation,  $W$  is invariant and  $U_i$  transforms to  $U_i W$ , which by (2.10) equals  $U_{i+1}$ . That is what  $U_i$  should transform into under the  $2\pi/n$  rotation. The combined global symmetry  $F$  plus gauge transformation  $W$  will be called  $F'$ .

To make contact with section 2.1, suppose  $G = SU(5)$ . Then in four-dimensional terms, the gauge group is  $SU(5)' \times SU(5)''$ , where one factor “lives” at  $P$  and the other at  $Q_1$ . The Wilson lines described above break  $SU(5)' \times SU(5)''$  to the subgroup of  $SU(5)$  that commutes with  $W$ . Of course, if

$$W = \begin{pmatrix} e^{2i\rho} & & & & \\ & e^{2i\rho} & & & \\ & & e^{2i\rho} & & \\ & & & e^{-3i\rho} & \\ & & & & e^{-3i\rho} \end{pmatrix}, \quad (2.11)$$

for some suitable  $n^{\text{th}}$  root of unity  $e^{i\rho}$ , then the unbroken group is the standard model subgroup  $SU(3) \times SU(2) \times U(1)$ .

The lattice gauge theory construction just sketched can (as in other discussions of deconstruction) be reinterpreted in terms of a set of Higgs fields that break  $SU(5)' \times SU(5)'' \times F$  down to  $SU(3) \times SU(2) \times U(1) \times F'$ . In fact, in moose [26] or quiver [27] theory, a unitary gauge group is placed at each lattice site and a “bifundamental” field  $\Phi$ , which in the present supersymmetric context would be a chiral superfield, is placed on each link. The expectation values of the  $\Phi$ 's need not in general be unitary matrices, but if the potential is suitable they will be unitary matrices obeying (2.10) (or they will be more general matrices leaving the same unbroken symmetries).

To complete the construction of a model, we place additional matter fields at the sites  $P$  and  $Q_1$ . For example, in the first model of section 2.1, the quarks and leptons

all originate from fields placed at  $P$ , while fields  $S, \tilde{S}$  which might be interpreted as the messenger fields of gauge-mediated supersymmetry breaking are placed at  $P$  and  $Q_1$ .

*Analog With  $D$  A Smooth Manifold*

As preparation for the next section, we will describe how one would obtain a similar model based on deconstruction of a smooth manifold rather than the singular space  $D$ .

The only important properties of  $D$  that we used in the above was that it has fundamental group  $\mathbf{Z}_n$  and has a discrete symmetry  $F$  of a suitable sort. For  $n > 2$ , a manifold of fundamental group  $\mathbf{Z}_n$  has at least dimension three. It is easy to give an example in dimension three. We start with a three-sphere  $Q_0$ , which we represent by complex numbers  $z_1, z_2$ , with  $|z_1|^2 + |z_2|^2 = 1$ . Then we consider the group  $L \cong \mathbf{Z}_n$  that acts by

$$L : z_i \rightarrow e^{2\pi i/n} z_i, \quad i = 1, 2. \quad (2.12)$$

Since  $L$  acts freely, the quotient is a manifold  $Q = Q_0/L = \mathbf{S}^3/\mathbf{Z}_n$  with fundamental group  $\mathbf{Z}_n$ .

So in  $SU(5)$  gauge theory, or lattice gauge theory, on  $Q$ , a configuration of minimal energy is determined by a holonomy matrix  $W$  with  $W^n = 1$ . With  $W$  chosen as in (2.11),  $SU(5)$  is broken to  $SU(3) \times SU(2) \times U(1)$ . Moreover,  $Q$  admits the action of a global symmetry  $F \cong \mathbf{Z}_n$  that acts by

$$F : z_1 \rightarrow z_1, \quad z_2 \rightarrow e^{2\pi i/n} z_2. \quad (2.13)$$

A flat gauge field on  $Q$  with holonomy  $W$  is  $F$ -invariant modulo a gauge transformation. To describe the necessary gauge transformation, or at least its key properties, in detail, let us look at the fixed points of  $F$ . These consist of two circles  $S_1$  and  $S_2$ , where  $S_1$  is defined by  $|z_1| = 1, z_2 = 0$ , and  $S_2$  is defined by  $z_1 = 0, |z_2| = 1$ .  $S_1$  is obviously left fixed by  $F$ , and  $S_2$  is also left fixed modulo the equivalence relation (2.12). We have defined  $Q$  as  $Q_0/L$ , where, to generate a flat vacuum gauge field with holonomy  $W$ , when we divide by  $L$  we make a gauge transformation by  $W$ . This tells us how  $F$  must act on the  $SU(5)$  gauge bundle. Since  $F$  leaves fixed  $S_1$  trivially, we can take  $F$  to act trivially on the fibers of the gauge bundle over  $S_1$ . But since  $F$  leaves  $S_2$  fixed modulo an element of  $L$  that is accompanied by a gauge transformation  $W$ , the transformation (2.13) must be accompanied on the fibers at  $S_2$  by a gauge transformation by  $W$ . So the unbroken symmetry  $F'$  is equivalent to  $F$  at  $S_1$ , but it is equivalent to  $F$  times the gauge transformation  $W$  at  $S_2$ .

Now we can construct a model. We postulate chiral superfields that are localized at points on  $Q$ , as opposed to gauge fields that propagate throughout  $Q$ . To be more precise, we localize the chiral superfields at points on  $S_1$  or  $S_2$ , so as to preserve the  $F'$  symmetry.<sup>4</sup>

To imitate the previous construction, we place Higgs fields transforming as  $\mathbf{5}$  of  $SU(5)$  on  $S_1$ , and we place Higgs fields transforming as  $\bar{\mathbf{5}}$  of  $SU(5)$  on  $S_2$ . We give the  $\mathbf{5}$  and  $\bar{\mathbf{5}}$  any  $F$  quantum numbers we want. Then under the unbroken discrete symmetry  $F'$ , the doublet and triplet in the  $\mathbf{5}$  transform the same way under  $F'$ , but the doublet and triplet in the  $\bar{\mathbf{5}}$  transform differently. This leads to the mechanism of doublet-triplet splitting that we have exploited earlier. By placing all quarks and leptons in  $\mathbf{10}$ 's and  $\bar{\mathbf{5}}$ 's that are supported at points on  $S_1$ , we can imitate the first model of section 2.1; by placing some on  $S_1$  and some on  $S_2$ , we can imitate the second model.

All this is in parallel with the two-dimensional example corresponding to the picture of figure 1. The circles  $S_1$  and  $S_2$  correspond respectively in that example to the point  $P$  and the boundary of the disc. In fact, those were the fixed points (modulo the equivalence relation) of the  $2\pi/n$  rotation that played the role of  $F$  in the two-dimensional case.

Deconstruction of the three-dimensional model could be accomplished by picking an  $F$ -invariant triangulation and using lattice gauge theory. Instead of going in that direction, we will now proceed to  $M$ -theory, where the type of construction that we have just sketched can arise naturally in compactification on a manifold of  $G_2$  holonomy.

### 3. Analog In $M$ -Theory On A Manifold Of $G_2$ Holonomy

It was predicted a quarter century ago that a maximal supergravity theory would exist in eleven dimensions [28], and the theory was constructed relatively soon afterwards [29]. Moreover, it has been known for nearly as long that  $\mathcal{N} = 1$  supersymmetry in four dimensions would arise in compactifying from eleven to four dimensions on a compact seven-manifold  $X$  of  $G_2$  holonomy.

This seems like an interesting starting point for making a model of the real world, which is certainly exceptional, and where there are hints of low energy supersymmetry.  $G_2$ , which is the smallest of the compact exceptional Lie groups, of rank two and dimension fourteen, is the only exceptional group that can be the holonomy of a (non-homogeneous) Riemannian manifold. Moreover, in the classification of holonomy groups

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<sup>4</sup> One could also consider including chiral superfields localized at a set of points making a non-trivial  $F'$  orbit, but we will omit this generalization.

of (non-homogeneous) Riemannian manifolds, there are several infinite series, and two exceptions –  $G_2$  in dimension seven and  $Spin(7)$  in dimension eight. Thus  $G_2$  holonomy is somewhat analogous to  $SU(3)$  holonomy, which is used in supersymmetric compactifications of string theory from ten to four dimensions, but is even more special.

All these facts suggest that as a starting point for models of particle physics, one should seriously consider compactification of eleven-dimensional supergravity or its refinement,  $M$ -theory, on a  $G_2$  manifold. Yet, until fairly recently, though  $G_2$  manifolds attracted attention, some early references being [30,31], model-building based on them was impractical. The reason is that if one assumes that  $X$  is smooth one runs into immediate difficulties, while if  $X$  is not smooth, supergravity is not valid and until recently one would not have known how to proceed.

The difficulties for smooth  $X$  are as follows. Since a compact manifold of  $G_2$  holonomy has no continuous symmetries, continuous gauge symmetries in compactification on such a manifold arise purely from the three-form field  $C$  of  $M$ -theory. It follows that the connected part of the gauge group is abelian, and that all massless chiral superfields are neutral. These features certainly clash with what we want for particle physics.

One way to get a non-abelian gauge group and chiral fermions from  $M$ -theory is to compactify on a manifold with boundary [32]. Here we want to go in a different direction, using the fact that there are other ways to get gauge fields and chiral fermions from singularities in geometry. For example, gauge fields can arise from  $A - D - E$  orbifold singularities [33], and massless chiral superfields can arise from conifold singularities [34] or from  $G_2$  analogs thereof that we will recall later.

The starting point for getting nonabelian gauge symmetry in this way is to consider  $M$ -theory on  $\mathbf{R}^7 \times \mathbf{R}^4/\Gamma$ , where  $\Gamma$  is a finite group of symmetries of  $\mathbf{R}^4$ . In fact, the rotation group of  $\mathbf{R}^4$  is  $SO(4) = SU(2)_L \times SU(2)_R$ , and we take  $\Gamma$  to be a subgroup of, say,  $SU(2)_L$ . Then  $\Gamma$  acts freely on  $\mathbf{R}^4$  except for a singularity at the origin  $\mathcal{O}$ , so  $\mathbf{R}^7 \times \mathbf{R}^4/\Gamma$  has the seven-dimensional singular set  $\mathbf{R}^7 \times \mathcal{O}$ .

The claim now [33] is that in  $M$ -theory on this singular space, nonabelian gauge fields propagate on  $\mathbf{R}^7 \times \mathcal{O}$ . The gauge group, depending on the choice of  $\Gamma$ , can be any of the groups  $SU(N)$ ,  $SO(2N)$ , and  $E_6$ ,  $E_7$ , or  $E_8$ . For example, to get gauge symmetry  $SU(5)$ , we take  $\Gamma$  to be  $\mathbf{Z}_5$ .

We have presented this so far as if the space on which the gauge fields propagate is supposed to be  $\mathbf{R}^7$ , but in general that might be compactified or partly compactified also. What is really important here is that gauge fields arise wherever there is a singularity that

looks locally like  $\mathbf{R}^4/\Gamma$ . For our purposes, consider  $M$ -theory on  $\mathbf{R}^4 \times X$ , where  $X$  is a singular manifold of  $G_2$  holonomy. Suppose that  $X$  has a singular set that looks locally like  $Q \times \mathbf{R}^4/\Gamma$ , for some three-manifold  $Q$ . Then in  $M$ -theory compactification on  $\mathbf{R}^4 \times X$ , the singular set is  $\mathbf{R}^4 \times Q$ . If  $\Gamma = \mathbf{Z}_5$ , we will get  $SU(5)$  gauge fields on  $\mathbf{R}^4 \times Q$ .

If moreover  $Q$  has fundamental group  $\mathbf{Z}_n$ , then as in [3] we can break  $SU(5)$  to the standard model  $SU(3) \times SU(2) \times U(1)$  by taking the gauge field on  $Q$  to be a flat connection with a non-trivial holonomy. In this way, we get a model that has a standard model gauge group at low energies, with low energy gauge couplings that obey the usual relation that holds in  $SU(5)$  supersymmetric GUT's, even though unification only strictly holds in the higher dimension.

We still do not have chiral fermions. In fact, if  $Q$  is smooth and  $X$  has only the orbifold singularities that we have already described, there will be no chiral fermions. To get chiral fermions in this construction, we should assume that  $Q$  passes through points at which the singularity of  $X$  is “worse” than an orbifold singularity. Singularities of  $X$  that will give a  $\mathbf{5}$  or  $\overline{\mathbf{5}}$  of  $SU(5)$  were described in [35], and singularities that give a  $\mathbf{10}$  or  $\overline{\mathbf{10}}$  were described in [17]. For our present purposes, the details of these singularities are not important. All that really matters is that in these constructions, one will get chiral superfields, transforming in suitable representations of  $SU(5)$ , and localized at points on  $Q$ . Note that in these constructions  $Q$  itself is smooth but passes through a point of  $X$  at which  $X$  has a “bad” singularity that generates charged chiral supermultiplets.

Now we can conceive of many models, depending on the choice of points on  $Q$  at which chiral supermultiplets are localized, and the quantum numbers of those multiplets. To solve the doublet-triplet splitting problem, we must be somewhat more specific. We assume that  $Q = \mathbf{S}^3/\mathbf{Z}_n$  and that  $X$  has a global  $\mathbf{Z}_n$  symmetry  $F$  which acts on  $Q$  as described in (2.13). If so, the singular points at which charged chiral superfields arise will form  $F$  orbits, and we will consider the case that these points all lie in the fixed set  $S_1 \cup S_2$  of  $Q$  that was described in section 2.2. Given this, we have all the ingredients to construct models like those of section 2 in the  $M$ -theory context: we assume the presence of a  $\mathbf{5}$  of Higgs bosons on  $S_1$ , a  $\overline{\mathbf{5}}$  on  $S_2$ , and additional multiplets containing standard model fermions on either  $S_1$  or  $S_2$  depending on what we want to get.

As has been explained elsewhere [16,17], concrete examples along these lines can be constructed using duality between  $M$ -theory on K3 and the heterotic string on  $\mathbf{T}^3$ . (A K3 surface is a four-manifold of  $SU(2)$  holonomy.) We start with a heterotic string model involving compactification on a six-manifold  $Y$  of  $SU(3)$  holonomy. If  $Y$  participates in

mirror symmetry (and it is believed that most manifolds of  $SU(3)$  holonomy do so) then in some limit of its moduli space,  $Y$  is fibered over some three-dimensional base  $Q$  with generic fiber  $\mathbf{T}^3$  [36]. By making fiber-wise the duality between the heterotic string on  $\mathbf{T}^3$  and  $M$ -theory on K3, we get an equivalent  $M$ -theory model with compactification on a manifold  $X$  of  $G_2$  holonomy that is fibered over  $Q$  with generic fiber K3.

If the heterotic string model has unbroken gauge symmetry  $SU(5)$  (possibly broken globally by holonomies of a flat connection), then the generic fiber of  $X$  has a  $\mathbf{Z}_5$  orbifold singularity and the locus of these singularities is a copy of  $Q$  on which  $SU(5)$  gauge fields propagate. In this construction, if we start in the heterotic string with a simply-connected six-manifold  $Y$ , then  $Q$  will be simply connected and will be, in fact, a copy of  $\mathbf{S}^3$ . But if  $Y$  is not simply connected,  $Q$  will be a quotient of  $\mathbf{S}^3$  such as  $Q = \mathbf{S}^3/\mathbf{Z}_n$ , the example considered in section 2.2. In this case, we can obtain in the  $M$ -theory framework models similar to those of section 2.2, solving the doublet-triplet splitting problem and achieving a realistically long lifetime for the proton.

While clearly this sort of model is quite similar to the models of section 2.2, there also are some differences. Some of these were noted at the end of the introduction. We may here note some additional differences:

(1) In the context of deconstruction, we can build any model we want; we have to impose anomaly cancellation by hand. In the  $M$ -theory framework, we are limited (in the choice of  $n$ , the arrangement of singularities, etc.) by the difficult problem of what singular manifolds of  $G_2$  holonomy actually exist. (For an account of much of the present knowledge of construction of smooth manifolds of  $G_2$  holonomy, see [37].) This may mean that there is more predictive power in principle, especially when one considers mechanisms of supersymmetry breaking, but it is hard to extract it. It can be shown that all singular  $G_2$  manifolds are such that the gauge anomalies cancel [16]. In the deconstructed models based on  $SU(5)' \times SU(5)''$ , one imposes anomaly cancellation as a constraint, and one has to separately cancel gauge anomalies in each factor. In the  $M$ -theory models, there is an anomaly inflow mechanism that can move anomalies from  $S_1$  to  $S_2$ , and triangle anomalies in general only cancel when summed over all multiplets supported on  $S_1$  or  $S_2$ .

(2) An  $M$ -theory model of the type we have described always has an axion with a coupling to standard model gauge fields (and conceivably solving the strong CP problem). This axion comes from the mode  $\int_Q C$  of the  $C$ -field. (Depending on the topology of  $X$ , there may be other axion-like fields, not coupling to standard model gauge fields but perhaps relevant to cosmology, coming from other modes of  $C$ . It is quite natural to have



many of these.) It is reasonable to expect by analogy with similar results for continuous gauge symmetries [16] that in the  $M$ -theory model,  $F$  is always anomaly-free, if one allows in general for a non-trivial transformation law of the axion under  $F$ . In the deconstructed models, there might not be an axion and the global symmetry  $F$  might be anomalous.

(3) In the  $M$ -theory models, Yukawa couplings contributing to quark and lepton masses always come from membrane instantons [38,17] (unless some of the points on  $Q$  that support chiral superfields coincide; then there may be classical contributions).<sup>5</sup> The quark and lepton masses can thus vary exponentially with the instanton volume, and it is natural, if some of the instantons have volume somewhat larger than the  $M$ -theory scale, to get some extremely light quarks and leptons. To get a large mass, such as the top quark mass, we have to assume that some singularities are nearby or perhaps even coincident (giving classical contributions). In the deconstructed models, there is an analogous but somewhat different mechanism, described in section 2.1, for suppressing the masses of some quarks and leptons; this arises when some fields can only receive mass as a result of unrenormalizable couplings.

#### *A Note On Yukawa Unification*

Finally, we note an interesting difference between this sort of  $M$ -theory model and many other models considered in string compactification. GUT models sometimes lead to relations among quark and lepton masses coming from unification [39]. For example, if the  $b$  quark and  $\tau$  lepton arise from the same  $\bar{\mathbf{5}}$  and  $\mathbf{10}$  of  $SU(5)$ , then the Yukawa couplings giving rise to their masses are related by  $SU(5)$  symmetry, giving a relation between them that is often called Yukawa unification. This leads to a relation between the  $b$  and  $\tau$  masses which, after allowing for renormalization from the GUT scale to the weak scale, agrees pretty well with experiment.

The analogous relations for the first two generations do not work well, however, and before going on let us note a simple way to avoid this problem in four-dimensional  $SU(5)$  models. We simply add an extra  $\mathbf{5}' \oplus \bar{\mathbf{5}}'$  of  $SU(5)$ , with GUT scale masses, but mixing with

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<sup>5</sup> The membrane instanton generically intersects  $Q$  in a graph that connects special points at which chiral superfields are supported. The amplitude for a membrane instanton contribution to the superpotential ties together the various superfields that enter the amplitude, and which may be supported at different points on  $Q$ , by parallel transport along the graph. The symmetry-breaking holonomy  $W$  may affect this parallel transport, producing phases for the various instanton contributions.

the  $\bar{\mathbf{5}} \oplus \mathbf{10}$  of, say, the first generation, in such a way that the observed down quark and electron are not  $SU(5)$  partners. To explain this in detail, we denote by  $\Phi$  a Higgs multiplet in the adjoint representation of  $SU(5)$  whose expectation value  $\langle \Phi \rangle$  breaks  $SU(5)$  to the standard model. We derive the mixing structure from generic renormalizable couplings

$$M\bar{\mathbf{5}}'\mathbf{5} + \Phi(a\bar{\mathbf{5}}' + b\bar{\mathbf{5}})\mathbf{5} \quad (3.1)$$

with mass  $M$  and couplings  $a, b$ ; we suppose  $M \sim a\Phi \sim b\Phi$ . Given such a structure, out of the  $\bar{\mathbf{5}}$  and  $\bar{\mathbf{5}}'$ , one field with down quark quantum numbers and one with electron quantum numbers pair up with the  $\mathbf{5}$  to get a GUT mass. But because of the coupling to  $\Phi$ , the heavy components of the  $\bar{\mathbf{5}}$  and  $\bar{\mathbf{5}}'$  are not  $SU(5)$  partners – different linear combinations are massive for down quarks and leptons. Likewise, one field with down quark quantum numbers and one field with electron quantum numbers will escape having GUT masses, but they will also not be  $SU(5)$  partners. Hence their Yukawa couplings to Higgs bosons are not related by  $SU(5)$  and the usual Yukawa unification will not hold. (Likewise many standard estimates concerning proton decay will be modified by this mixing.) Since standard Yukawa unification does work for the third generation, one might want to impose discrete symmetries such that (to some approximation) this sort of mixing only affects the first two generations.

In many string theory compactifications, this sort of mixing occurs (with the role of the heavy fields being played by Kaluza-Klein excitations or massive string modes) and the standard Yukawa unification does not hold. For example, in the original Calabi-Yau model [3], despite its similarity to four-dimensional GUT's, the usual GUT relations among Yukawa relations are not valid: the unified group is only present in ten dimensions, and by the time one reduces to four dimensions, one cannot make sense of the question of which down quark is the  $SU(5)$  or  $E_6$  partner of the electron. By contrast, in the  $M$ -theory models discussed here, even though  $SU(5)$  is broken, the special points in  $Q$  support complete  $SU(5)$  multiplets. So there is always a natural notion of which down quark is the  $SU(5)$  partner of a given charged lepton, namely the one that is supported at the same point on  $Q$ .

Whether the Yukawa couplings obey  $SU(5)$  relations is a more subtle question. Since the Yukawa couplings come from nonlocal effects (membrane instantons), they might conceivably see  $SU(5)$  breaking by Wilson lines. However, to the extent that each Yukawa coupling comes mainly from a single type of instanton, the Wilson lines, which contribute

phases to the amplitudes (by a mechanism mentioned in the last footnote), would not disturb the  $SU(5)$  mass relations. (Wilson lines might give different phases to different membrane instantons contributing to a given Yukawa coupling, and thereby spoil  $SU(5)$  relations among the couplings if more than one instanton contributes.) So in this situation we do have a framework for why some quark and lepton masses might obey approximate  $SU(5)$  relations.

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