Emergence of Maximal Symmetry

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An emergent global symmetry of the composite sector (called maximal symmetry) can soften the ultraviolet behavior of the Higgs potential and also significantly modify its structure. We explain the conditions for the emergence of maximal symmetry as well as its main consequences and present two simple implementations. In both cases the emergence of maximal symmetry is enforced by the structure of the gauge symmetries.

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The discovery of the Higgs boson has been a milestone for particle physics [1,2]. However, the potential for such an elementary scalar particle is generically sensitive to physics at extremely high scales, rendering the Higgs potential unstable to quantum corrections. One can impose additional symmetries to eliminate this ultraviolet (UV) sensitivity. Besides supersymmetry [3] or discrete symmetry like twin parity [4] or trigonometric parity [5], one widely considered possibility is a spontaneously broken (approximate) global symmetry, with the Higgs identified as one of the pseudo-Nambu-Goldstone bosons (pNGB) of this symmetry breaking [6–8] (for reviews, see Refs. [9,10]). Particular implementations of this global symmetry breaking can forbid the UV divergences of the Higgs potential. Some of the leading ideas along this direction are collective symmetry breaking and little Higgs [11] models, dimensional deconstruction [12,13], warped extra dimensions [14–16], and the Weinberg sum rule for a composite Higgs [17].

Recently a new concept has been proposed as an alternative to these methods mentioned above; the UV divergences of the Higgs potential from the top sector are absent because of "maximal symmetry" [18]. The structure of the low energy effective Lagrangian differs from the generic case: maximal symmetry forbids Higgs corrections for the effective kinetic terms of the top quark which source the UV divergence and are often the leading sources for the quadratic term in the Higgs potential. Although maximal symmetry is simple, elegant, and can have many model building applications, the exact nature of maximal symmetry and its emergence in the low-energy effective action have remained somewhat mysterious.

In this Letter, we show that the origin of maximal symmetry is actually very simple: it is simply an enhanced global symmetry of the composite sector. Generically composite Higgs models are based on a coset G/H corresponding to the $G \to H$ symmetry breaking pattern and the composite sector only has an H symmetry. Whenever H is enhanced to G we will obtain a maximally symmetric model. After explaining the basic principles behind maximal symmetry we illustrate them by constructing the simplest two site models. We show that maximal symmetry can be easily enforced by the gauge symmetries of the model, indicating that maximal symmetry is secretly a remnant of some of the gauge symmetries broken at higher energies. We also discuss the realization of maximal symmetry in warped extra dimensional models. Note that our second implementation ("minimal maximal symmetry") is a brand new setup that has never been discussed before. We finally briefly discuss the structure of the Higgs potential and find that a light Higgs can be obtained without light top partners in the model with minimal maximal symmetry.

Maximal symmetry is the enhancement of the spontaneously broken G/H symmetry back to the full G in some sector of the composites. Generically composites form representations of the unbroken group H, and the original

G symmetry is not implemented in the composite sector. In the most general situation the composites do not even have to fill out a complete G representation. There may, however, be sectors of composite fields (for example, the fermionic top partners) where the composites themselves still form a complete G multiplet, hence the composite sector may have an emergent enhanced G global symmetry. This enhanced global symmetry is maximal symmetry, which can play an important role in softening and enforcing particular structures on the induced Higgs potential. While the effects of maximal symmetry are similar to collective breaking usually employed in composite Higgs models, conceptually it is quite different and also has distinct consequences. Collective breaking is an ingenious mechanism for softening the divergences of the Higgs potential by ensuring that one needs several different couplings turned on simultaneously to fully break the global symmetry protecting the Higgs boson. Maximal symmetry on the other hand is a true unbroken global symmetry of (a sector) of the theory, and it is this unbroken symmetry that will ensure a finite Higgs potential and nontrivial relations among the various terms in it (leading to a reduced tuning). We will see in the concrete examples below how maximal symmetry is explicitly implemented and how its effects differ from collective breaking in N-site models [19,20]. In particular we will see that maximal symmetry can easily be used in a two-site model rendering the Higgs potential finite, while for ordinary collective breaking one needs at least 3 sites. We will also show the effect of maximal symmetry in removing one of the form factors of the low-energy effective theory (which is usually responsible for the log divergences in the deconstructed models), and how the absence of this form factor will imply that these models have significantly less tuning than traditional composite Higgs models.

For concreteness we will consider the $G = SO(5)$ and $H = SO(4)$ symmetry breaking pattern corresponding to the minimal choice that incorporates a custodial symmetry for the standard model (SM). The Higgs field is contained in the nonlinear sigma field U which transforms as [21,22]

$$U \to gUh^{\dagger}, \tag{1}$$

where $g \in G$ is an element of the linearly realized full G symmetry while $h \in H$ is the nonlinearly realized shift symmetry. Thus the U field can also be interpreted as the field connecting $SO(5)$ symmetry of the elementary sector with the spontaneously broken $SO(5)$ symmetry of the composite sector: it transforms under an $SO(5)_{\rm el} \times SO(5)_{\rm co}$ symmetry, where the composite sector breaks $SO(5)_{\rm co}$ to $SO(4)$. Either of $SO(5)_{\rm el}$ and $SO(5)_{\rm co}$ is sufficient to fully protect the pNGBs from acquiring any potential. We thus need to break both $SO(5)$'s but in such a manner that some remnant bigger than $SO(4)$ is left over. There are two simple options emerging, depending on the embedding of the SM fermions into the global symmetries.

1. Both the left-handed top doublet q_L and the right handed top t_R are embedded into $SO(5)_{\rm el}$. This is the standard assumption, corresponding to the SM fermions being mainly elementary. The embedding of these fields into incomplete $SO(5)_{\rm el}$ multiplets breaks the elementary symmetry, but does not say anything about the structure of the composite sector. The enhancement of the global symmetries will depend entirely on the structure of the composite fields. To achieve our goal we need to preserve an $SO(5)$ symmetry that does not coincide with the original $SO(5)_{\rm co}$. The original proposal of maximal symmetry is exactly that: an $SO(5)_{\rm co'}$ symmetry that appears in the composite sector, where the $SO(5)_{\rm co'}$ is not identical to $SO(5)_{\rm co}$.

2. The second option is when q_L is embedded in the elementary sector, but t_R in the composite sector. Since t_R is an $SU(2)_L$ singlet this can be easily achieved by simply making t_R a singlet under $SO(4)_{\rm co}$. In this case already the embedding of q_L and t_R will have the right symmetry breaking pattern of $SO(5)_{\rm el} \times SO(5)_{\rm co}$ to ensure that a Higgs potential will be generated. If the remaining composites maintain any form of $SO(5)$ symmetry [which now could also coincide with the original $SO(5)_{\rm co}$] a softening of the UV behavior of the Higgs potential is expected. We call this new possibility the minimal realization of maximal symmetry.

Next let us explain how maximal symmetry restricts the form of the low-energy Lagrangian, leading to the elimination of the Higgs dependence of the effective kinetic terms. Consider first the case from Ref. [18] when both q_L and t_R are embedded in the elementary sector. For concreteness we assume that they are both in fundamentals of $SO(5)_{\rm el}$ transforming as $\Psi_{q_L} \to g_{\rm el}\Psi_{q_L}$ and $\Psi_{t_R} \to g_{\rm el}\Psi_{t_R}$. We also assume that the coset G/H is a so-called "symmetric space" [which means that there exists a Higgs-parity operator V determining the pattern of the breaking of $SO(5)_{\rm co}$]. In this case one can always construct the linearly realized pNGB matrix $\Sigma' = UVU^{\dagger} = U^2V$, which transforms linearly under the full set of global symmetries $\Sigma' \to g_{\rm el}\Sigma' g_{\rm el}^{\dagger}$. By integrating out the composite sector, the effective Lagrangian for the elementary fields invariant under $SO(5)_{\rm el}$ will be [18]

$$\begin{aligned}\mathcal{L}_{\rm eff} = {} & \bar{\Psi}_{q_L}\not{p}[\Pi_0^L(p) + \Pi_1^L(p)\Sigma']\Psi_{q_L} - \bar{\Psi}_{q_L}M_1^t(p)\Sigma'\Psi_{t_R} \\ & + \bar{\Psi}_{t_R}\not{p}[\Pi_0^R(p) + \Pi_1^R(p)\Sigma']\Psi_{t_R} + \text{H.c.},\end{aligned} \tag{2}$$

where the form factors $\Pi_{0,1}^{L/R}(p)$ and M_1^t encode the effects of the composite sector. One can then trace back the action of the composite symmetries in the Lagrangian (2) by noting that the dressed elementary fields $U^{\dagger}\Psi_{q_L,t_R}$ transform under the chirally enhanced composite global symmetries $SO(5)_{{\rm co},L} \times SO(5)_{{\rm co},R}$ as $U^{\dagger}\Psi_{q_L,t_R} \to g_{{\rm co},L,R}U^{\dagger}\Psi_{q_L,t_R}$. The Higgs dependent kinetic term $\bar{\Psi}_{q_L}\not{p}\Sigma'\Psi_{q_L}$ can be rewritten in terms of the dressed fields as $(\bar{\Psi}_{q_L}U)V(U^\dagger\Psi_{q_L})$ and is only invariant under the $SO(4)_{\rm co}$ symmetry, implying $\Pi_1^{L,R}=0$. It is the vanishing of these form factors that will imply the softening of the Higgs potential and also the reduced tuning in these models. Note that these form factors generically do not vanish in composite Higgs models with collective breaking. However M_1^t term $\bar{\Psi}_{q_L}\Sigma'\Psi_{t_R}=(\bar{\Psi}_{q_L}U)V(U^\dagger\Psi_{t_R})$ breaks chiral composite symmetries to maximal symmetry $SO(5)_{\rm co'}$ defined by $g_{{\rm co},L}Vg_{{\rm co},R}^\dagger=V$. We see that the $SO(5)_{\rm co'}$ global symmetry can forbid the Higgs dependent kinetic terms and allow the effective Yukawa coupling. For more details on the cancellation on the structure of the model and the cancellation of divergences, see the Supplemental Material [23].

Let us now consider the second possibility, not discussed so far in the literature, which we will refer to as the minimal maximal symmetry. In this case q_L is still embedded in the elementary sector, however, t_R is now assumed to be transforming under the global symmetries of the composite sector. For simplicity we will again assume that q_L and t_R are embedded into fundamental representations of $SO(5)_{\rm el}$ and $SO(5)_{\rm co}$ respectively, transforming as $\Psi_{q_L}\to g_{\rm el}\Psi_{q_L}$ and $\Psi_{t_R}\to g_{\rm co}\Psi_{t_R}$ with $g_{\rm el}\in SO(5)_{\rm el}$ and $g_{\rm co}\in SO(5)_{\rm co}$. Since the composite sector must be $H\equiv SO(4)\subset SO(5)_{\rm co}$ invariant, Ψ_{t_R} should be a full H representation to keep H unbroken. After integrating out the composite sector the general form of the effective Lagrangian invariant under the $SO(5)_{\rm el}$ global symmetry can be written as

$$\mathcal{L}_{\rm eff}=\bar{\Psi}_{q_L}\not{p}[\Pi_0^L(p)+\Pi_1^L(p)\Sigma']\Psi_{q_L}+\bar{\Psi}_{t_R}\not{p}\Pi_0^R(p)\Psi_{t_R} + \bar{\Psi}_{q_L}M_1^t(p)U\Psi_{t_R}+\text{H.c.}, \tag{3}$$

differing slightly from Eq. (2): the form factor Π_1^R is automatically vanishing, while the M_1^t mass term has a U insertion connecting the elementary and composite sectors, rather than the Σ'. Following the discussion in the first case, if any $SO(5)$ subgroup of the chirally enhanced composite global symmetries, defined as $U^\dagger\Psi_{q_L}\to g_{{\rm co},L}U^\dagger\Psi_{q_L}$ and $\Psi_{t_R}\to g_{{\rm co},R}\Psi_{t_R}$, is unbroken, the form factor Π_1^L will again be forbidden. However, the M_1^t term is automatically invariant under this symmetry and will be allowed. Note that in some sense this scenario is even more powerful than the traditional implementation of maximal symmetry. For the minimal maximal symmetry, however, *any* $SO(5)$ subgroup of the chiral global symmetries is sufficient—the modified M_1^t term will always be left invariant. However the embedding of the q_L and t_R into Ψ_{q_L} and Ψ_{t_R} will now explicitly break both the elementary and the composite global symmetries, and a Higgs potential will be generated.

We will present the simplest two site models corresponding to both implementations of maximal symmetry discussed above. These also represent the simplest realistic finite EWSB models. One of the main takeaways from these models is that gauge symmetry can be used to enforce the relations needed for the appearance of maximal symmetry, and no special tuning or coincidence of parameters is needed to achieve the maximally symmetric limit.

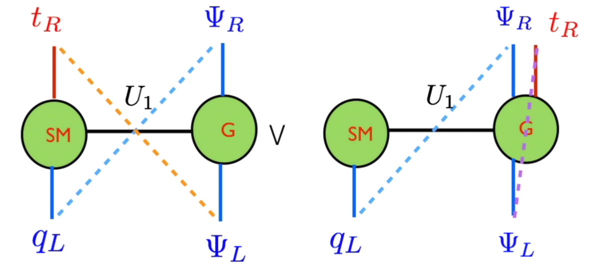

FIG. 1. Moose diagrams for the two-site models. Left, ordinary maximal symmetry; Right, minimal maximal symmetry.

Ordinary maximal symmetry.—In the two-site model with maximal symmetry, the global symmetry is $SO(5)_1\times SO(5)_2$, and the link field U_1 which breaks it to the diagonal subgroup, is in the bi-fundamental representation of the global symmetry. The $SU(2)_L\times U(1)_Y$ subgroup of $SO(5)_1$ and the entire $SO(5)_2$ are fully gauged, as shown in the left panel in Fig. 1. A scalar field with VEV $V=\text{diag}(1,1,1,1,-1)$ at the second site is introduced to break the gauge symmetry at the second site to $SO(4)$. The linear pNGB field Σ corresponding to this breaking can be parametrized as $\Sigma=U'VU'^\dagger$, where U' is nonlinear sigma field of coset space $SO(5)_2/SO(4)$. Gauging the global symmetries will eat some of the pNGBs such that we are left with a single set of pNGBs corresponding to the $SO(5)_1/SO(4)$ coset. These uneaten NGBs can be described by the linear sigma field $\Sigma'=UVU^\dagger$ with $U=U_1U'$.

In the fermion sector, we introduce the SM fermions t_L, t_R, b_L at the first site, while a $SO(5)_2$ Dirac fermion multiplet Ψ at the second site. The gauge symmetry $SO(5)_2$ guarantees an enhanced $SO(5)_{2L}\times SO(5)_{2R}$ chiral global symmetry for Ψ in the limit of vanishing Dirac mass terms. On the other hand its Yukawa coupling to Σ breaks it to $SO(5)_{2'}$ which keeps the VEV V invariant $g_LVg_R^\dagger=V$. To obtain maximal symmetry, $SO(5)_{2'}$ should be preserved, which requires the mass of Ψ is only from the $SO(5)_2/SO(4)$ breaking, which could be enforced by a discrete Z_2 or Z_3 symmetry. The general fermion interactions read

$$\mathcal{L}_f=\bar{q}_Li\not{D}q_L+\bar{\Psi}i\not{D}\Psi+\bar{t}_Ri\not{D}t_R-\epsilon_L\bar{\Psi}_{q_L}U_1\Psi_R - M\bar{\Psi}_L\Sigma\Psi_R-\epsilon_R\bar{\Psi}_LU_1^\dagger\Psi_{t_R}+\text{H.c.}, \tag{4}$$

where Ψ is in the 5 representation of $SO(5)_2$ gauge symmetry and $\Psi_{q_L}=(ib_L,b_L,it_L,-t_L,0)/\sqrt{2}$, $\Psi_{t_R}=(0,0,0,0,t_R)$ are embedded in the 5 representation of global $SO(5)_1$. If we turn off any of the three Yukawa couplings above, the Higgs shift symmetry is restored, which indicates that the only dependence on the Higgs field will be $y_t \sim \epsilon_L \epsilon_R M$ and the $\Pi_1^{L,R} \sim \epsilon_{L,R}^2$ form factors in Eq. (2) vanish. Thus the Higgs potential is finite at the one-loop level.

Minimal maximal symmetry.—The two site model can also easily realize the minimal implementation of maximal symmetry described above. For this we can choose the same basic model with two sites and same group structure. The main difference will be that the singlet top t_R will be introduced at the second site $SO(5)_2$ as a gauge singlet, as shown in the right panel in Fig. 1. In addition the $SO(5)_2/SO(4)$ breaking will this time be via a VEV $\mathcal{V} = (0,0,0,0,1)$ in the vector 5 of $SO(5)_2$ with its corresponding sigma field $\mathcal{H}' = U'\mathcal{V}$. The uneaten NGBs are still in the coset $SO(5)_1/SO(4)$, which can again be described by $\mathcal{H} = U\mathcal{V}$ and $U = U_1 U'$. The bare mass term of Dirac fermion Ψ can be introduced to breaks its chiral symmetry to $SO(5)_2$ as maximal symmetry. The most general Lagrangian then is

$$\mathcal{L}_f = \bar{q}_L i\not{D} q_L + \bar{\Psi} i\not{D}\Psi + \bar{t}_R i\not{D} t_R - \epsilon_L \bar{\Psi}_{q_L} U_1 \Psi_R - M\bar{\Psi}_L \Psi_R - \epsilon_R \bar{\Psi}_L \mathcal{H}' t_R + \text{H.c.} \tag{5}$$

Following the same analysis, the Higgs potential is still dependent on the product of mixing Yukawa couplings and Dirac mass. Again we can see that because there is a $SO(5)$ global symmetry in the Ψ sector the effective kinetic terms of SM field are independent on Higgs field.

Maximal symmetry from extra dimensions.—These models can be easily promoted to full extra dimensional theories by identifying the first site with a UV brane and the second site with an IR brane. We can use the standard warped extra dimensional model based on a slide of AdS_5 ending on UV and IR branes, and a bulk $SO(5) \times U(1)_X$ gauge group as in the holographic MCHM [16]. The key new ingredient is to keep the interactions in the fermion sector at the IR brane invariant under the global symmetry $SO(5)_{\text{co}'}$ [the bulk gauge symmetry automatically enforces that the bulk multiplets for the top doublet and singlet both have a global $SO(5)$ symmetry in the bulk]. To ensure this, we must impose $SO(5)$ preserving boundary conditions on the IR brane for the fermions. For example, if we embed the quarks into **5**'s of $SO(5)$, we should impose all + boundary conditions for the LH fermions in the **5** that contains the SM LH doublet, while for the **5** containing the SM RH fermions we should impose the + boundary conditions for the RH fields. To ensure the proper fermions masses via the Higgs mechanism we still need to add some brane localized masses. To ensure that the remaining global symmetry is $SO(5)_{\text{co}'}$ we need to twist these boundary masses using the Higgs parity operator V:

$$S_{\text{mix}} = \frac{1}{g_5^2} \int_{\text{IR}} d^4x \sqrt{g^{(\text{ind})}} \tilde{m} (\bar{\Psi}_{1L} V \Psi_{2R} + \text{H.c.}), \tag{6}$$

where Ψ_1 is the bulk fermion containing the SM LH doublets, and Ψ_2 contains a RH SM fermion. This construction will ensure the presence of maximal symmetry and all its consequences on the Higgs potential. A small variation of this model can also implement the minimal maximal symmetry presented above.

Finally, we explain the utility of maximal symmetry in achieving a phenomenologically viable Higgs potential. It is usually parametrized, using the variable $s_h \equiv \sin[\langle h \rangle / f] \ll 1$, and expanded to leading order as

$$V(h) = -(\gamma_f - \gamma_g) s_h^2 + \beta_f s_h^4, \tag{7}$$

where γ_f, β_f are the contributions from the top sector and β_g is the contribution from the gauge sector. If $\gamma_f - \gamma_g$ and β_f are positive, the Higgs will acquire a VEV, $\xi \equiv s_h^2 = (\gamma_f - \gamma_g)/(2\beta_f)$. To achieve a small ξ, the coefficient of the s_h^2 term has to be suppressed via cancellations. The tuning measuring this cancellation is around $\Delta \approx \gamma_f/(\xi \beta_f)$.

In composite Higgs models based on deconstruction or Holographic Higgs models the Higgs potential is usually finite. However, γ_f and β_f are from the leading and subleading contributions of the top effective kinetic terms so they will have a different dependence on the top Yukawa coupling y_t: $\gamma_f \sim \mathcal{O}(y_t)$ and $\beta_f \sim \mathcal{O}(y_t^2)$. It will result in double tuning for a viable Higgs potential around $\Delta \sim (g_f/y_t) 1/\xi$ [24], where $g_f \equiv M_f/f$ and M_f is the top partner mass.

In the CHM with maximal symmetry, the Higgs potential from the top sector originates entirely from the top Yukawa coupling and is finite. To get a small ξ, the main source of tuning is from the cancellation between γ_f and γ_g. In the original maximally symmetric model [18] γ_f and β_f are of the same order in the top Yukawa coupling, thus the tuning is minimal, $\Delta \sim 1/\xi$. Numerically a tuning of $\Delta \approx 13$ is needed to obtain the correct Higgs mass with $\xi = 0.05$, $M_f > 1.5$ TeV and vector partners heavier than 2.5 TeV. Experimental verification of the predictions of this model has been studied in Ref. [26].

We want to emphasize that in all of the CHMs discussed so far in this section, the Higgs mass explicitly depends on the top partner mass, implying that the top partner mass must be light, around $g_f \approx 1$, to obtain a 125 GeV Higgs. However for the case of minimal maximal symmetry this situation changes. Because of the different choice of embeddings the effective top Yukawa term is proportional to s_h (vs proportional to s_{2h} in ordinary maximal symmetry), as a result of which $\gamma_f \sim \mathcal{O}(y_t^2)$ and $\beta_f \sim \mathcal{O}(y_t^4)$. Although there is still double tuning, since β_f is at $\mathcal{O}(y_t^4)$, $\beta_f \sim y_t^4 f^4/(4\pi)^2$, it is not sensitive to the top partner mass, which leads to the insensitivity of the Higgs mass to top partner mass $m_h^2 = 8\beta_f \xi / f^2 \sim y_t^4 \langle h \rangle^2 / (2\pi^2)$. While in the simplest models the Higgs usually turns out to be somewhat light ($m_h \approx 100$ GeV for $M_f \approx 10f$), one can be easily enhance the Higgs mass while still significantly suppressing the tuning by producing an independent Higgs quartic coupling (for a simple recent proposal see Refs. [27,28]). Numerically in such a model the tuning is $\Delta \approx 40$ to achieve the realistic Higgs potential for $\xi = 0.1$, top partners and vector partners heavier than 2 and 4 TeV, respectively, which is usually much smaller than that in a traditional composite Higgs model [24]. For numerical results see the Supplemental Material [23].

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