Higgs, Top, and Bottom Mass Predictions in Finite Unified Theories

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Abstract

All-loop Finite Unified Theories (FUTs) are $N = 1$ supersymmetric Grand Unified Theories (GUTs) based on the principle of reduction of couplings, which have a remarkable predictive power. The reduction of couplings implies the existence of renormalization group invariant relations among them, which guarantee the vanishing of the beta functions at all orders in perturbation theory in particular $N = 1$ GUTs. In the soft breaking sector these relations imply the existence of a sum rule among the soft scalar masses. The confrontation of the predictions of a $SU(5)$ FUT model with the top and bottom quark masses and other low-energy experimental constraints leads to a prediction of the light Higgs-boson mass in the range $M_h \sim 121 - 126$ GeV, in remarkable agreement with the discovery of the Higgs boson with a mass around $\sim 125.7$ GeV. Also a relatively heavy spectrum with coloured supersymmetric particles above $\sim 1.5$ TeV is predicted, consistent with the non-observation of those particles at the LHC.

1 Introduction

In the last thirty years a large and sustained effort has been made to achieve a unified description of all interactions. Among the main efforts in this direction are superstring theories, and non-commutative geometry. The two approaches have common unification targets and share similar hopes for exhibiting improved renormalization properties in the ultraviolet (UV) as compared to ordinary field theories. Among the numerous important developments in both frameworks, it is worth noting two conjectures of utmost importance that signal the developments in certain directions in string theory. The conjectures refer to (i) the duality among the 4-dimensional $N = 4$ supersymmetric Yang-Mills theory and the type IIB string theory on $AdS_5 \times S^5$ [1]; the former being the maximal $N = 4$ supersymmetric Yang-Mills theory is known to be UV all-loop finite theory [2,3], (ii) the possibility of “miraculous” UV divergence cancellations in 4-dimensional maximal $N = 8$ supergravity leading to a finite theory, as has been confirmed in a remarkable 4-loop calculation [4–8]. However, despite the importance of having frameworks to discuss quantum gravity in a self-consistent way and possibly to construct there finite theories, it is very interesting too to search for the minimal realistic framework in which finiteness can take place. In addition, the main goal expected from a unified description of interactions by the particle physics community is to understand the present day large number of free parameters of the Standard Model (SM) in terms of a few fundamental ones. In other words, to achieve reduction of couplings at a more fundamental level.

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To reduce the number of free parameters of a theory, and thus render it more predictive, one is usually led to introduce a symmetry. Grand Unified Theories (GUTs) are very good examples of such a procedure [9–13]. GUTs can also relate the Yukawa couplings among themselves, again $SU(5)$ provided an example of this by predicting the ratio $M_\tau/M_b$ [14] in the SM. A natural extension of the GUT idea is to find a way to relate the gauge and Yukawa sectors of a theory, that is to achieve Gauge-Yukawa Unification (GYU) [15–17]. This can be done by searching for renormalization group invariant (RGI) relations [16–35] holding below the Planck scale down to the GUT scale, leading to more predictive theories as compared to supersymmetric GUTs [16, 21–26]. An outstanding feature of the use of RGI relations is that one can guarantee their validity to all-orders in perturbation theory by studying the uniqueness of the resulting relations at one-loop [27, 28]. Even more remarkable is the fact that it is possible to find RGI relations among couplings that guarantee finiteness to all-orders in perturbation theory [29–31].

The above programme, called Gauge–Yukawa unification scheme, applied in the dimensionless couplings of supersymmetric GUTs, such as gauge and Yukawa couplings, predicted correctly, among others, the top quark mass in the finite and in the minimal $N = 1$ supersymmetric $SU(5)$ GUTs [21–23].

The search for RGI relations was extended to the soft supersymmetry breaking sector (SSB) of these theories [26,36], which involves parameters of dimension one and two. The $\beta$-functions of the parameters of the softly broken theory can be expressed in terms of partial differential operators involving the dimensionless parameters of the unbroken theory, which in turn can be transformed into total derivative operators [37–40]. It is possible to do this in the RGI surface which is defined by the solution of the reduction equations.

Concerning the boundary conditions for the soft breaking terms, the first attempts involved using a “universal” value for the scalar masses, but this led to phenomenological problems, of which the worst was a they lead to charge and/or colour breaking minima deeper than the standard vacuum [41]. Then it was realized that in $N = 1$ Gauge–Yukawa unified theories there exists a RGI sum rule for the soft scalar masses at lower orders; at one-loop for the non-finite case [42] and at two-loops for the finite case [32]. The sum rule manages to overcome the phenomenological problems of the universal boundary conditions. It was also proven [40] that the sum rule for the soft scalar masses is RGI to all-orders for both the general as well as for the finite case.

In here we review an $SU(5)$ finite model and its predictions coming both from the dimensionless sector, namely the top and quark masses and $\tan \beta$, as well as the ones coming from the dimensionful sector, which are the SUSY spectrum and the Higgs masses. We take into account the restrictions resulting from the low-energy observables [35, 43], which include the recent values of BR($B_s \to \mu^+\mu^-$) and the value of the light Higgs boson mass.

2 Finiteness

Finiteness can be understood by considering a chiral, anomaly free, $N = 1$ globally supersymmetric gauge theory based on a group $G$ with gauge coupling constant $g$. The superpotential of the theory is given by

$$ W = \frac{1}{2} m^{ij} \Phi_i \Phi_j + \frac{1}{6} C^{ijk} \Phi_i \Phi_j \Phi_k , \quad (1) $$

where $m^{ij}$ (the mass terms) and $C^{ijk}$ (the Yukawa couplings) are gauge invariant tensors and the matter field $\Phi_i$ transforms according to the irreducible representation $R_i$ of the gauge group $G$. All the one-loop $\beta$-functions of the theory vanish if the $\beta$-function of the gauge coupling $\beta_g^{(1)}$, and the anomalous dimensions of the Yukawa couplings $\gamma_i^{(1)}$, vanish, i.e.

$$ \sum_i \ell(R_i) = 3C_2(G), \quad \frac{1}{2} C_{ipq} C^{jpiq} = 2\delta_i^j g^2 C_2(R_i) , \quad (2) $$

100
where \( \ell(R_i) \) is the Dynkin index of \( R_i \), and \( C_2(G) \) is the quadratic Casimir invariant of the adjoint representation of \( G \). These conditions are also enough to guarantee two-loop finiteness [44]. A striking fact is the existence of a theorem [29–31] that guarantees the vanishing of the \( \beta \)-functions to all-orders in perturbation theory. This requires that, in addition to the one-loop finiteness conditions (2), the Yukawa couplings are reduced in favour of the gauge coupling to all-orders (see [34] for details). Alternatively, similar results can be obtained [45–47] using an analysis of the all-loop NSVZ gauge beta-function [48, 49].

Next consider the superpotential given by (1) along with the Lagrangian for soft supersymmetry breaking (SSB) terms

\[
-\mathcal{L}_{\text{SB}} = \frac{1}{6} h^{ijk} \phi_i \phi_j \phi_k + \frac{1}{2} b^{ij} \phi_i \phi_j + \frac{1}{2} (m^2)^i_j \phi^* \phi_j + \frac{1}{2} M \lambda \lambda + \text{h.c.},
\]

where the \( \phi_i \) are the scalar parts of the chiral superfields \( \Phi_i \), \( \lambda \) are the gauginos and \( M \) their unified mass, \( h^{ijk} \) and \( b^{ij} \) are the trilinear and bilinear dimensionful couplings respectively, and \( (m^2)^i_j \) the soft scalars masses. Since we would like to consider only finite theories here, we assume that the gauge group is a simple group and the one-loop \( \beta \)-function of the gauge coupling \( g \) vanishes. We also assume that the reduction equations admit power series solutions of the form

\[
C^{ijk} = g \sum_n \rho^{ijk}_n g^{2n}.
\]

According to the finiteness theorem of ref. [29–31, 50], the theory is then finite to all orders in perturbation theory, if, among others, the one-loop anomalous dimensions \( \gamma^{(1)}_i \) vanish. The one- and two-loop finiteness for \( h^{ijk} \) can be achieved through the relation [51]

\[
h^{ijk} = -MC^{ijk} + \cdots = -M\rho^{ijk}_0 g + O(g^5),
\]

where \( \cdots \) stand for higher order terms.

In addition it was found that the RGI SSB scalar masses in Gauge-Yukawa unified models satisfy a universal sum rule at one-loop [42]. This result was generalized to two-loops for finite theories [32], and then to all-loops for general Gauge-Yukawa and finite unified theories [40]. From these latter results, the following soft scalar-mass sum rule is found [32]

\[
\frac{(m_i^2 + m_j^2 + m_k^2)}{MM^I} = 1 + \frac{g^2}{16\pi^2} \Delta^{(2)} + O(g^4)
\]

for \( i, j, k \) with \( \rho^{ijk}_0 \neq 0 \), where \( m_i^2 \) are the scalar masses and \( \Delta^{(2)} \) is the two-loop correction

\[
\Delta^{(2)} = -2 \sum_l \left[ (m_l^2/MM^I) - (1/3) \right] \ell(R_l),
\]

which vanishes for the universal choice, i.e. when all the soft scalar masses are the same at the unification point. This correction also vanishes in the models considered here.

3 SU(5) Finite Unified Theories

Finite Unified Models have been studied for already two decades. A realistic two-loop finite \( SU(5) \) model was presented in [52], and shortly afterwards the conditions for finiteness in the soft susy breaking sector at one-loop [44] were given. Since finite models usually have an extended Higgs sector, in order to make them viable a rotation of the Higgs sector was proposed [53]. The first all-loop finite theory was studied in [21, 22], without taking into account the soft breaking terms. Naturally, the concept of finiteness was extended to the soft breaking sector, where also one-loop finiteness implies two-loop
finiteness [51], and then finiteness to all-loops in the soft sector of realistic models was studied [38, 54], although the universality of the soft breaking terms lead to a charged lightest SUSY particle (LSP). This fact was also noticed in [55], where the inclusion of an extra parameter in the Higgs sector was introduced to alleviate it. With the derivation of the sum-rule in the soft supersymmetry breaking sector and the proof that it can be made all-loop finite the construction of all-loop phenomenologically viable finite models was made possible [32, 40].

Here we will study an all-loop Finite Unified Theories with $SU(5)$ gauge group, where the reduction of couplings has been applied to the third generation of quarks and leptons. An extension to three families, and the generation of quark mixing angles and masses in Finite Unified Theories has been addressed in [56], where several examples are given. These extensions are not considered here. Realistic Finite Unified Theories based on product gauge groups, where the finiteness implies three generations of matter, have also been studied [57].

The particle content of the model we will study consists of the following supermultiplets: three $(\bar{5} + 10)$, needed for each of the three generations of quarks and leptons, four $(\bar{5} + 5)$ and one $24$ considered as Higgs supermultiplets. When the gauge group of the finite GUT is broken the theory is no longer finite, and we will assume that we are left with the MSSM.

Thus, a predictive Gauge-Yukawa unified $SU(5)$ model which is finite to all orders, in addition to the requirements mentioned already, should also have the following properties:

1. One-loop anomalous dimensions are diagonal, i.e., $\gamma_i^{(1)} \propto \delta_i^2$.
2. Three fermion generations, in the irreducible representations $\bar{5}_i, 10_i$ $(i = 1, 2, 3)$, which obviously should not couple to the adjoint $24$.
3. The two Higgs doublets of the MSSM should mostly be made out of a pair of Higgs quintet and anti-quintet, which couple to the third generation.

The superpotential which describes the model is [21, 22, 32]

$$W = \sum_{i=1}^{3} \left[ \frac{1}{2} g_i^{10} 10_i 10_i H_3 + g_i^{d} 10_i \bar{5}_i \overline{H}_1 \right] + g_{23}^{24} 10_2 10_3 H_4 + g_{23}^{24} 10_2 5_3 \overline{H}_4 + g_{32}^{24} 10_3 5_2 \overline{H}_4$$

$$+ \sum_{a=1}^{4} g_a^H H_a \overline{24}_a + \frac{g^\lambda}{3} (24)^3,$$  \hspace{1cm} (8)

where $H_a$ and $\overline{24}_a$ $(a = 1, \ldots, 4)$ stand for the Higgs quintets and anti-quintets.

After the reduction of couplings, the symmetry is enhanced, and we are left with the following superpotential [58], we will from now on refer to this model as FUTB

$$W = \sum_{i=1}^{3} \left[ \frac{1}{2} g_i^{10} 10_i 10_i H_3 + g_i^{d} 10_i \bar{5}_i \overline{H}_1 \right] + g_{23}^{24} 10_2 10_3 H_4$$

$$+ g_{23}^{24} 10_2 5_3 \overline{H}_4 + g_{32}^{24} 10_3 5_2 \overline{H}_4 + g_2^f H_2 \overline{24}_2 + g_3^f H_3 \overline{24}_3 + \frac{g^\lambda}{3} (24)^3,$$  \hspace{1cm} (9)

The non-degenerate and isolated solutions to $\gamma_i^{(1)} = 0$ give us:

$$\left( g_i^{10} \right)^2 = \frac{8}{5} g^2, \left( g_i^{d} \right)^2 = \frac{6}{5} g^2, \left( g_i^{f} \right)^2 = \frac{4}{5} g^2,$$  \hspace{1cm} (10)

$$\left( g_{23}^{24} \right)^2 = \left( g_{32}^{24} \right)^2 = \frac{3}{5} g^2, \left( g_{23}^{24} \right)^2 = \frac{4}{5} g^2, \left( g_{32}^{24} \right)^2 = \frac{3}{5} g^2,$$
known usually as the corrections coming from bottom squark-gluino loops and top squark-chargino loops \[63\], \(\sim [15, 16, 33, 61]\). For the bottom quark mass we use the value at \(M = 4\%\) as the solution most compatible with this experimental constraints. Although similar, the mechanism is not identical to minimal \(SU(5)\), since we have an extended Higgs sector. Thus, after the gauge symmetry of the GUT theory is broken we are left with the MSSM, with the boundary conditions for the third family given by the finiteness conditions, while the other two families are not restricted.

4 Predictions of Low Energy Parameters

Since the gauge symmetry is spontaneously broken below \(M_{GUT}\), the finiteness conditions do not restrict the renormalization properties at low energies, and all it remains are boundary conditions on the gauge and Yukawa couplings, see Eq. (10), the \(h = -MC\) relation, see Eq. (5), and the soft scalar-mass sum rule at \(M_{GUT}\), as applied in the model Eq. (11). Thus we examine the evolution of these parameters according to their RGEs up to two-loops for dimensionless parameters and at one-loop for dimensionful ones with the relevant boundary conditions. Below \(M_{GUT}\) their evolution is assumed to be governed by the MSSM. We further assume a unique supersymmetry breaking scale \(M_s\) (which we define as the geometric mean of the stop masses) and therefore below that scale the effective theory is just the SM.

We now review the predictions of the model with the experimental data, starting with the heavy quark masses see ref. [35] for more details. We use for the top quark the value for the pole mass [60]

\[ m_t^{\text{exp}} = (173.2 \pm 0.9) \text{ GeV}, \]

and we recall that the theoretical prediction for \(m_t\) of the present framework may suffer from a correction of \(\sim 4\% [15, 16, 33, 61]\). For the bottom quark mass we use the value at \(M_Z\) [62]

\[ m_b(M_Z) = (2.83 \pm 0.10) \text{ GeV}, \]

to avoid uncertainties that come from the further running from the \(M_Z\) to the \(m_b\) mass.

In fig.1 we show the \textbf{FUTB} model predictions for \(m_t\) and \(m_b(M_Z)\) as a function of the unified gaugino mass \(M\), for the two cases \(\mu < 0\) and \(\mu > 0\). In the value of the bottom mass \(m_b\), we have included the corrections coming from bottom squark-gluino loops and top squark-chargino loops [63], known usually as the \(\Delta_b\) effects. The bounds on the \(m_b(M_Z)\) and the \(m_t\) mass clearly single out the sign \(\mu < 0\), as the solution most compatible with this experimental constraints. Although \(\mu < 0\) is already challenged by present data of the anomalous magnetic moment of the muon \(a_\mu\) [64, 65], a heavy SUSY spectrum as the one we have here (see below) gives results for \(a_\mu\) very close to the SM result, and thus cannot be excluded.

We now analyze the impact of further low-energy observables on the model \textbf{FUTB} with \(\mu < 0\). As additional constraints we consider the following observables: the rare \(b\) decays \(\text{BR}(b \rightarrow s\gamma)\) and \(\text{BR}(B_s \rightarrow \mu^+\mu^-)\).
Higgs, Top, and Bottom Mass Predictions in Finite Unified Theories

Fig. 1: The bottom quark mass at the Z boson scale (left) and top quark pole mass (right) are shown as function of $M$, the unified gaugino mass.

Fig. 2: The lightest Higgs mass, $M_h$, as function of $M$ for the model FUTB with $\mu < 0$, see text.

For the branching ratio $\text{BR}(b \to s\gamma)$, we take the value given by the Heavy Flavour Averaging Group (HFAG) is [66]

$$\text{BR}(b \to s\gamma) = (3.55 \pm 0.24^{+0.09}_{-0.30} \pm 0.03) \times 10^{-4}.$$  \hspace{1cm} (14)

For the branching ratio $\text{BR}(B_s \to \mu^+\mu^-)$, the SM prediction is at the level of $3 \times 10^{-9}$, while we use an experimental upper limit of

$$\text{BR}(B_s \to \mu^+\mu^-) = 4.5 \times 10^{-9} \hspace{1cm} (15)$$

at the 95% C.L. [67] This is in relatively good agreement with the recent direct measurement of this quantity by CMS and LHCb [68]. As we do not expect a sizable impact of the new measurement on our results, we stick for our analysis to the simple upper limit.

For the lightest Higgs mass prediction we use the code FeynHiggs [69–72]. The prediction for $M_h$ of FUTB with $\mu < 0$ is shown in Fig. 2, where the constraints from the two $B$ physics observables are taken into account. The lightest Higgs mass ranges in

$$M_h \sim 121 – 126 \text{ GeV}, \hspace{1cm} (16)$$
where the uncertainty comes from variations of the soft scalar masses. To this value one has to add at least $\pm 2 \text{ GeV}$ coming from unknown higher order corrections \cite{71}. \footnote{We have not yet taken into account the improved $M_h$ prediction presented in \cite{73} (and implemented into the most recent version of \texttt{FeynHiggs}), which will lead to an upward shift in the Higgs boson mass prediction.} We have also included a small variation, due to threshold corrections at the GUT scale, of up to $5\%$ of the FUT boundary conditions. The masses of the heavier Higgs bosons are found at higher values in comparison with our previous analyses \cite{35,74–76}. This is due to the more stringent bound on $\text{BR}(B_s \to \mu^+ \mu^-)$, which pushes the heavy Higgs masses beyond $\sim 1 \text{ TeV}$, excluding their discovery at the LHC. We furthermore find in our analysis that the lightest observable SUSY particle (LOSP) is either the stau or the second lightest neutralino, with mass starting around $\sim 500 \text{ GeV}$.

As the crucial new ingredient we take into account the recent observations of the Higgs boson discovered at LHC \cite{77–80}. We impose a constraint on our results to the Higgs mass of

$$M_h \sim 126.0 \pm 1 \pm 2 \text{ GeV},$$

where $\pm 1$ comes from the experimental error and $\pm 2$ corresponds to the theoretical error, and see how this affects the SUSY spectrum. \footnote{In this analysis the new $M_h$ evaluation \cite{73} may have a relevant impact on the restrictions on the allowed SUSY parameter space shown below.} Constraining the allowed values of the Higgs mass this way puts a limit on the allowed values of the unified gaugino mass, as can be seen from Fig. 2. The red lines correspond to the pure experimental uncertainty and restrict $2 \text{ TeV} \lesssim M \lesssim 5 \text{ TeV}$. The blue line includes the additional theory uncertainty of $\pm 2 \text{ GeV}$. Taking this uncertainty into account no bound on $M$ can be placed. However, a substantial part of the formerly allowed parameter points are now excluded. This in turn restricts the lightest observable SUSY particle (LOSP), which turns out to be the light scalar tau. In Fig. 3 the effects on the mass of the LOSP are demonstrated. Without any Higgs mass constraint all coloured points are allowed. Imposing $M_h = 126 \pm 1 \text{ GeV}$ only the green (light shaded) points are allowed, restricting the mass to be between about $500 \text{ GeV}$ and $2500 \text{ GeV}$. The lower values might be experimentally accessible at the ILC with $1000 \text{ GeV}$ center-of-mass energy or at CLIC with an energy up to $\sim 3 \text{ TeV}$. Taking into account the theory uncertainty on $M_h$ also the blue (dark shaded) points are allowed, permitting the LOSP mass up to $\sim 4 \text{ TeV}$. If the upper end of the parameter space were realized the light scalar tau would remain unobservable even at CLIC.

\textbf{Fig. 3:} The mass of the LOSP is presented as a function of $M$. Shown are only points that fulfill the $B$ physics constraints. The green (light shaded) points correspond to $M_h = 126 \pm 1 \text{ GeV}$, the blue (dark shaded) points have $M_h = 126 \pm 3 \text{ GeV}$, and the red points have no $M_h$ restriction.
Table 1: A representative spectrum of a light FUTB, $\mu < 0$ spectrum, compliant with the $B$ physics constraints. All masses are in GeV.

The full particle spectrum of model FUTB with $\mu < 0$, compliant with quark mass constraints and the $B$-physics observables is shown in Fig. 4. In the upper (lower) plot we impose $M_h = 126 \pm 3(1)$ GeV. Without any $M_h$ restrictions the coloured SUSY particles have masses above $\sim 1.8$ TeV in agreement with the non-observation of those particles at the LHC [81–83]. Including the Higgs mass constraints in general favours the lower part of the SUSY particle mass spectra, but also cuts away the very low values. Neglecting the theory uncertainties of $M_h$ (as shown in the lower plot of Fig. 4) permits SUSY masses which would remain unobservable at the LHC, the ILC or CLIC. On the other hand, large parts of the allowed spectrum of the lighter scalar tau or the lighter neutralinos might be accessible at CLIC with $\sqrt{s} = 3$ TeV. Including the theory uncertainties, even higher masses are permitted, further weakening the discovery potential of the LHC and future $e^+e^-$ colliders. A numerical example of the lighter part of the spectrum is shown in Table 1. If such a spectrum were realized, the coloured particles are at the border of the discovery region at the LHC. Some uncoloured particles like the scalar taus, the light chargino or the lighter neutralinos would be in the reach of a high-energy Linear Collider.

5 Conclusions

It is a remarkable fact that many interesting ideas that have survived various theoretical and phenomenological tests, as well as the solution to the UV divergencies problem, find a common ground in the framework of $\mathcal{N} = 1$ Finite Unified Theories, which we have briefly described here. These theories, which are based on the principle of reduction of couplings (expressed via RGI relations among couplings and masses) show very promising features. From the theoretical side they solve the problem of ultraviolet divergencies in a minimal way, whereas on the phenomenological side, they provide strict selection rules for choosing realistic models which lead to testable predictions. The success of predicting the top-quark mass [21–24, 26, 84] was extended to the predictions of the Higgs masses and the supersymmetric spectrum of the MSSM [35]. The predictions of the FUTB $SU(5)$ finite model in light of the recent discovery of a Higgs-like state at the LHC and on the new bounds on the branching ratio $\text{BR}(B_s \to \mu^+\mu^-)$ shows that compared to our previous analysis [35], the new bound on $\text{BR}(B_s \to \mu^+\mu^-)$ excludes values for the heavy Higgs bosons masses below $1 \sim$ TeV, and in general allows only a very heavy SUSY spectrum. The Higgs mass constraint favours the lower part of this spectrum, with SUSY masses ranging from $\sim 500$ GeV up to the multi-TeV level, where the lower part of the spectrum could be accessible at the ILC or CLIC [43].

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Fig. 4: The upper (lower) plot shows the spectrum after imposing the constraint $M_h = 126 \pm 3 \,(1) \,\text{GeV}$ of model FUTB with $\mu < 0$, where the points shown are in agreement with the quark mass constraints and the $B$-physics observables. The light (green) points on the left are the various Higgs boson masses. The dark (blue) points following are the two scalar top and bottom masses, followed by the lighter (gray) gluino mass. Next come the lighter (beige) scalar tau masses. The darker (red) points to the right are the two chargino masses followed by the lighter shaded (pink) points indicating the neutralino masses.

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Higgs, Top, and Bottom Mass Predictions in Finite Unified Theories


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108
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