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# The Significance of the Heavy Top Quark[1]

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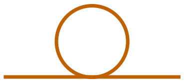
**Abstract.** Experiment shows that the top quark is far heavier than the other elementary fermions. This finding has stimulated research on theories of electroweak and flavor symmetry breaking that include physics beyond the standard model. Efforts to accommodate a heavy top quark within existing frameworks have revealed constraints on model-building. Other investigations have started from the premise that a large top quark mass could signal a qualitative difference between the top quark and other fermions, perhaps in the form of new interactions peculiar to the top quark. Such new dynamics may also help answer existing questions about electroweak and flavor physics. This talk explores the implications of the heavy top quark in the context of weakly-coupled (e.g. SUSY) and strongly-coupled (e.g. technicolor) theories of electroweak symmetry breaking.

## INTRODUCTION

Two outstanding mysteries in particle theory are the cause of electroweak symmetry breaking and the origin of flavor symmetry breaking by which the quarks and leptons obtain their diverse masses. The Standard Model of particle physics, based on the gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$ accommodates both symmetry breakings by including a fundamental weak doublet of scalar ("Higgs") bosons $\phi = \binom{\phi^+}{\phi^0}$ with potential function $V(\phi) = \lambda \left(\phi^\dagger \phi - \frac{1}{2}v^2\right)^2$. However the Standard Model provides no explanation of the dynamics responsible for the generation of mass. Furthermore, the scalar sector suffers from two serious problems. The scalar mass is unnaturally sensitive to the presence of physics at any higher scale $\Lambda$ (e.g. the Planck scale or a grand-unification scale):



$$\Rightarrow \; M_H^2 \; \propto \; \Lambda^2$$

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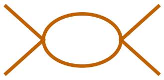
[1] Talk given at Beyond The Standard Model V, 29 April – 4 May, 1997, Balholm, Norway.

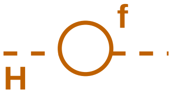
This is known as the gauge hierarchy problem. In addition, if the scalar must provide a good description of physics up to arbitrarily high scale (i.e., be fundamental, not composite), the scalar's self-coupling ($\lambda$) is driven to zero



$$\Rightarrow \beta = \frac{3\lambda^2}{2\pi^2} > 0$$

at finite energy scales. That is, the scalar field theory is free (or "trivial"). Then the scalar cannot fill its intended role: if $\lambda = 0$, the electroweak symmetry is not spontaneously broken. It is, thus, necessary to seek the origin of mass in physics that lies beyond the Standard Model.

One intriguing possibility is to introduce supersymmetry [1]. The gauge structure of the minimal supersymmetric version of the Standard Model (MSSM) is identical to that of the Standard Model, but each ordinary fermion (boson) is paired with a new boson (fermion) called its "superpartner" and two Higgs doublets are needed to provide mass to all the ordinary fermions. Each loop of ordinary particles contributing to the higgs boson's mass is now countered by a loop of superpartners. If the masses of the ordinary

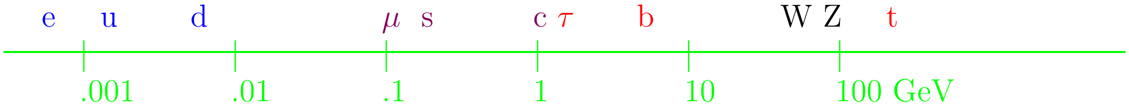


$$\Rightarrow \delta M_H^2 \sim \frac{g_f^2}{4\pi^2}(m_f^2 - m_s^2)$$

particles and superpartners are sufficiently close, the gauge hierarchy can be stabilized [2] . In addition, supersymmetry relates the scalar self-coupling to gauge couplings, so that triviality is not a concern.

Another interesting class of models involve dynamical electroweak symmetry breaking [3]. In these theories, a new strong gauge interaction with $\beta < 0$ (e.g technicolor) breaks the chiral symmetries of a set of massless fermions $f$ at a scale $\Lambda \sim 1\text{TeV}$. If the fermions carry appropriate electroweak quantum numbers, the resulting condensate $\langle \bar{f}_L f_R \rangle \neq 0$ breaks the electroweak symmetry as desired. The logarithmic running of the strong gauge coupling renders the low value of the electroweak scale (i.e. the gauge hierarchy) natural. The absence of fundamental scalar bosons obviates concerns about triviality.

How is one to choose among the various models ? Consider a rough graph of the masses of the known fermions and gauge bosons:



The top quark is singled out [4]: it is the heaviest known elementary particle, with a mass of order the electroweak scale, $v \sim 246\text{GeV}$, and is far heavier than its weak partner ($b$). This suggests that the top quark may afford us insight about existing models of electroweak physics and may even play a special role in electroweak and flavor symmetry breaking.

# THE TOP QUARK MAKES A DIFFERENCE

The large mass of the top quark has illuminated aspects of existing theories of electroweak and flavor physics. We review some opportunities and constraints the top quark has provided for supersymmetric models and theories of dynamical electroweak symmetry breaking.

## Electroweak Symmetry Breaking in SUSY Models

A challenge for supersymmetric models is to explain why the Higgs scalar develops a negative mass-squared (so that the electroweak symmetry breaks) while the scalar partners of the ordinary fermions do not (so that color and electromagnetism are preserved). The heavy top quark provides a solution.

In many types of models (e.g. the constrained MSSM (CMSSM), models of dynamical supersymmetry breaking) the mass-squared of the higgs is related to that of the sfermions, and is therefore positive at scales ($M_X$) well above the weak scale [5]

$$M^2_{h,H}(M_X) = m_0^2 + \mu^2 \qquad M^2_{\tilde f}(M_X) = m_0^2$$

Moving towards lower scales, the masses of the higgs ($M_h$) and of the top squarks ($\tilde M_{t_R}, \tilde M_{Q^3_L}$) evolve under the renormalization group [6]:

$$\frac{d}{d\ln(q)} \begin{pmatrix} M_h^2 \\ \tilde M^2_{t_R} \\ \tilde M_{Q^3_L}{}^2 \end{pmatrix} = -\frac{8\alpha_s}{3\pi} M_3^2 \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \frac{\lambda_t^2}{8\pi^2} (\tilde M^2_{Q^3_L} + \tilde M^2_{t_R} + M_h^2 + A^2_{o,t}) \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix}$$

Clearly, the top quark's large Yukawa coupling $\lambda_t$ is important and the mass-squared of the higgs $h$ is affected more than that of the squarks. The approximate solution for the light higgs mass-squared at scale $q$ is

$$M_h^2(q) = M_h^2(M_X) - \frac{3}{8\pi^2}\lambda_t^2 \left(\tilde M^2_{Q^3_L} + \tilde M^2_{t_R} + M_h^2 + A^2_{o,t}\right) ln\left(\frac{M_X}{q}\right)$$

For a top quark mass $m_t \sim 175$ GeV, the higgs mass-squared is driven negative near the electroweak scale [6], while those of the squarks are not. As desired, the electroweak symmetry breaks while color and electromagnetism survive.

## Effects on the Higgs Spectrum of SUSY Models

After electroweak symmetry breaking, the higgs spectrum of the MSSM includes two neutral scalar bosons. The tree-level upper bound on the mass of the lighter one ($h$) is $M_h < M_Z|\cos(2\beta)|$. This would appear to forbid $\tan\beta \sim 1$ and lies quite close to the experimental lower bound on $m_h$.

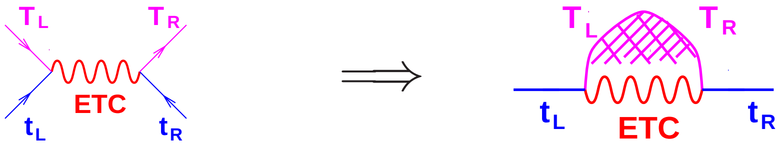
Radiative corrections involving the heavy top quark and its superpartners provide a resolution. For $\tan\beta > 1$, the bound on $M_h$ becomes [7]

$$M_h^2 \lesssim M_Z^2 \cos^2(2\beta) + \frac{3G_f}{\sqrt{2}\pi^2}\, m_t^4 \; ln\left(\frac{\tilde{m}^2}{m_t^2}\right)$$

so that $M_h \lesssim 130$ GeV and $\tan\beta \sim 1$ (the $U(1)_R$ symmetric limit [8] or "light gaugino-higgsino window" [9]) is still viable.

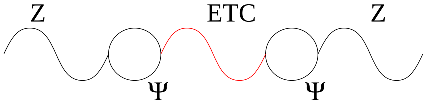
## Oblique Corrections in Dynamical Models

Extended technicolor (ETC) is an explicit realization of dynamical electroweak symmetry breaking and fermion mass generation. One starts with a strong gauge group (technicolor) felt only by a set of new massless fermions (technifermions) and extends the technicolor gauge group to a larger (ETC) group under which ordinary fermions are also charged. At a scale $M$, ETC breaks to its technicolor subgroup and the gauge bosons coupling ordinary fermions to technifermions acquire a mass of order $M$. At a scale $\Lambda_{TC} < M$ the technicolor coupling becomes strong enough to form a technifermion condensate and break the electroweak symmetry. Because the massive ETC gauge bosons couple the ordinary fermions to the condensate, the ordinary fermions acquire mass too. The top quark's mass, e.g., comes from



and its size is $m_t \approx (g_{ETC}^2/M^2)\langle T\bar{T}\rangle \approx (g_{ETC}^2/M^2)(4\pi v^3)$. Thus the scale $M$ must satisfy $M/g_{ETC} \approx 1.4$ TeV in order to produce $m_t = 175$ GeV.

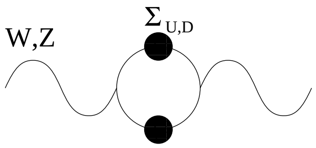
Several difficulties arise when one tries to balance the need to create a wide range of ordinary fermion masses against the requirement of keeping the oblique correction $\Delta\rho$ small. First are the so-called "direct" contributions [10] to $\Delta\rho$. The ETC sector must violate weak isospin in order to make $m_t \gg m_b$. This can induce dangerous technifermion ($\Psi$) contributions to $\Delta\rho$:



$$\Rightarrow \qquad \Delta\rho \approx 12\% \cdot \left(\frac{\sqrt{N_D}F_{TC}}{250\ \text{GeV}}\right)^2 \cdot \left(\frac{1\ \text{TeV}}{M/g_{ETC}}\right)^2 .$$

To satisfy the experimental constraint $\Delta\rho \leq 0.4\%$, one might consider making the ETC boson heavy. This requires $(M/g_{ETC}) > 5.5\text{TeV}(\sqrt{N_D}F_{TC}/250\text{GeV})$, which is too heavy to produce $m_t \sim 175\text{GeV}$. A better alternative [3] is to arrange for separate dynamical sectors to break the electroweak symmetry and produce the bulk of $m_t$. Then the technifermions contributing to $\Delta\rho$ can satisfy $\sqrt{N_D}F_{TC} \ll 250\text{GeV}$.

There are also "indirect" contributions [3] to $\Delta\rho$ from isospin- violating



splittings between technifermion dynamical masses $\Sigma_U(0), \Sigma_D(0)$. Again, a solution is to have the $t$ and $b$ quarks obtain only part of their masses from technicolor. This can keep the technifermion mass splitting small enough at low energies $\Delta\Sigma(0) \simeq m_t(M_{ETC}) - m_b(M_{ETC}) \ll m_t(0) - m_b(0)$. However the $t$ and $b$ quarks must feel some additional strong interaction not shared by the light fermions or technifermions, which can generate $m_t \gg m_b \gg m_{light\ quark}$ as sketched in Figure 1. We will revisit these ideas later.

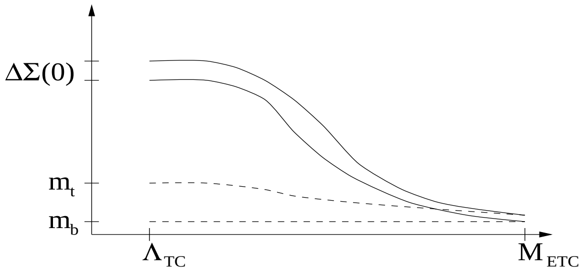
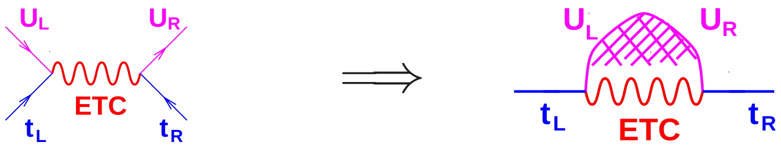


**FIGURE 1.** Dynamical technifermion and fermion masses sketched as a function of momentum. This illustrates [3] the scenario where the bulk of $m_t$ and $m_b$ comes from a new strong interaction not felt by the technifermions or other quarks.

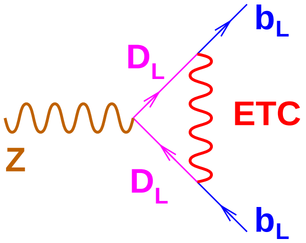
## Corrections to $Zb\bar{b}$ in Dynamical Models

While the contributions to $\Delta\rho$ just discussed are physically distinct from generation of $m_t$, the very ETC boson responsible for $m_t$ makes potentially large contributions to $R_b$. Consider the simplest ETC models, those in which the ETC and weak gauge groups commute and the ETC bosons carry no weak charge. The ETC boson responsible for generating the top quark mass couples to the current $\xi(\bar{T}_L\gamma_\mu\psi_L) + \xi^{-1}(\bar{U}_R\gamma_\mu t_R)$ where $\xi$ is an ETC Clebsch, $\psi \equiv (t, b)$, and $T \equiv (U, D)$ is a technifermion doublet. The top quark mass comes from



and is of order $m_t \equiv (g^2_{ETC}/M^2)(4\pi v^3)$. This implies [11] that the size of the typical vertex correction arising from exchange of this ETC boson is proportional to the top mass: $g^2_{ETC}v^2/M^2 \approx m_t/4\pi v$.

In particular, this ETC boson causes a radiative correction to the $Zb\bar{b}$ vertex that shifts the $Zb\bar{b}$ coupling by $\delta g_L = \frac{e}{4\sin\theta\cos\theta}\frac{g_{ETC}^2 v^2}{M^2}$ . As we have seen, this is proportional to $m_t$. Because $m_t$ is so large, $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is decreased by $\approx 5\%$ relative to the standard model prediction; such a value of $R_b$ has been excluded by experiment [12]. Hence, these "commuting" ETC models are ruled out [11].



# THE TOP QUARK MAY BE DIFFERENT

We next consider whether the top quark's large mass implies that the $t$ quark has unique new interactions. Such scenarios provide alternative mechanisms of electroweak and flavor symmetry breaking and are experimentally testable.

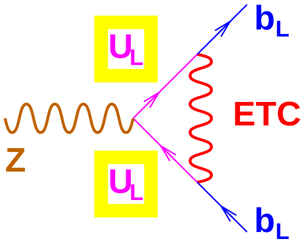
## New Weak Interactions for the Top Quark

To start, we return to extended technicolor. Our discussion of $R_b$ did not rule out the possibility of "non-commuting" models in which $SU(2)_W$ is embedded in $G_{ETC}$ so that the ETC bosons carry weak charge. To build such a model, one must balance the requirements of providing a range of quark masses against the need to ensure that the weak interactions are universal at low energies. As discussed in [13], this leads to separate weak interactions for the 3rd generation fermions ($SU(2)_{heavy}$) and the light fermions ($SU(2)_{light}$) and the symmetry-breaking pattern

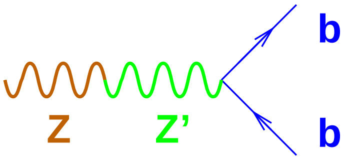
$$\begin{array}{c} G_{ETC} \times SU(2)_{light} \\ \downarrow \\ G_{TC} \times SU(2)_{heavy} \times SU(2)_{light} \\ \downarrow \\ G_{TC} \times SU(2)_{weak} \end{array}$$

The result is a model where the top quark has non-standard weak interactions.

Our first concern is the value of $R_b$ this model predicts. The ETC boson responsible for creating $m_t$ is now a weak doublet coupling to $\xi(\bar{U}_L\gamma_\mu\psi_L) + \xi^{-1}(\bar{T}_R\gamma_\mu t_R)$. This gives a direct radiative correction to the $Zb\bar{b}$ vertex which is of the same magnitude but opposite sign to the correction in commuting models [13]. That alone would not make $R_b$ compatible with experiment. But in addition, mixing of the $Z$



bosons from the two weak gauge groups gives another correction to the $Zb\bar{b}$ vertex which essentially brings $R_b$ back to the standard model value. Thus non-commuting ETC can be consistent with the measured value of $R_b$.



Non-standard top quark weak interactions may be detectable in single top-quark production at TeV33 [14]. The ratio of cross-sections $R_\sigma \equiv \sigma(\bar{p}p \to tb)/\sigma(\bar{p}p \to l\nu)$ can be measured (and calculated) to an accuracy [15] of at least $\pm 8\%$. A non-commuting ETC model might alter $R_\sigma$ in several ways. Mixing of the two $W$ bosons alters the light $W$'s couplings to the final state fermions. Exchange of both heavy and light $W$ bosons contributes to the cross-sections. But exchange of the ETC boson that generates $m_t$ does **not** modify the $Wtb$ vertex, because the boson does not couple to all of the required fermions: $(t_R, b_R, U_R, D_R)$. In the case of $R_b$, the vertex and boson mixing effects canceled, leaving $R_b$ at the standard model value; here the boson mixing effects are not canceled and can yield a visible **increase** in $R_\sigma$ (see Figure 2).

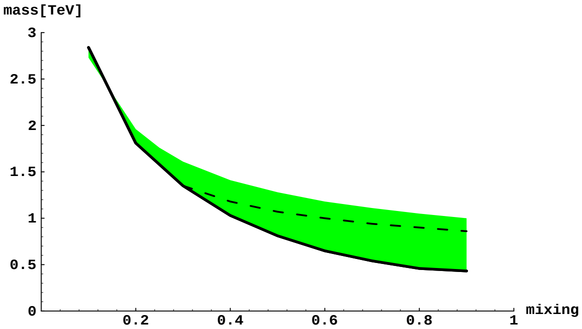


**FIGURE 2.** The axes are heavy $W$ mass and degree of mixing of the two weak gauge groups in a non-commuting ETC model. The shaded region is the area consistent with low-energy data in which $R_\sigma$ would be increased by at least 16% [13].

## New Strong Interactions for the Top Quark

To build a dynamical symmetry breaking model that provides both electroweak symmetry breaking and a large $m_t$, it has been suggested [16] that all or some of electroweak symmetry breaking could be caused by a top quark condensate ($\langle \bar{t}t \rangle \neq 0$). One way to implement this is to start with a spontaneously broken strong gauge interaction that distinguishes top from the other quarks. Suppose the model includes an $SU(3)_H$ for the $t$ (and $b$) and an $SU(3)_L$ for the other quarks which break to their diagonal subgroup (identified with $SU(3)_{QCD}$ at a scale $M$. At energies below $M$, exchange of the heavy gauge bosons yields a new four-fermion interaction can cause top quark condensation.

$$\mathcal{L} \supset -\frac{4\pi\kappa}{M^2}\left(\bar{t}\gamma_\mu\frac{\lambda^a}{2}t\right)^2$$

The simplest "topcolor-assisted technicolor" model [17] incorporating top condensates has the following gauge group and symmetry-breaking pattern.

$$\begin{array}{c} G_{TC}\times SU(3)_H\times SU(3)_L\times SU(2)_W\times U(1)_H\times U(1)_L \\ \downarrow \quad M \gtrsim 1TeV \\ G_{TC}\times SU(3)_C\times SU(2)_W\times U(1)_Y \\ \downarrow \quad \Lambda_{TC}\sim 1TeV \\ SU(3)_C\times U(1)_{EM} \end{array}$$

The groups $G_{TC}$ and $SU(2)_W$ are ordinary technicolor and weak interactions; the strong and hypercharge groups labeled "H" couple to 3rd-generation fermions and have stronger couplings than the "L" groups coupling to light fermions The separate $U(1)$ groups ensure that the bottom quark will not condense when the top quark does. Below the scale $M$, the Lagrangian includes effective interactions for $t$ and $b$:

$$-\frac{4\pi\kappa_{tc}}{M^2}\left[\overline{\psi}\gamma_\mu\frac{\lambda^a}{2}\psi\right]^2-\frac{4\pi\kappa_1}{M^2}\left[\frac{1}{3}\overline{\psi_L}\gamma_\mu\psi_L+\frac{4}{3}\overline{t_R}\gamma_\mu t_R-\frac{2}{3}\overline{b_R}\gamma_\mu b_R\right]^2$$

So long as the following relationship is satisfied (where the critical value is $\kappa_c \approx 3\pi/8$ in the NJL approximation [18])

$$\kappa^t=\kappa_{tc}+\frac{1}{3}\kappa_1>\kappa_c>\kappa_{tc}-\frac{1}{6}\kappa_1=\kappa^b$$

only the top quark will condense and become very massive [17].

Topcolor-assisted technicolor models have several appealing features [19] [3]. Technicolor causes most of the electroweak symmetry breaking, with the top condensate contributing a decay constant $f \sim 60$ GeV; this prevents $\Delta\rho$ from being too large, as mentioned earlier. So long as the $U(1)_H$ charges of the technifermions are isospin-symmetric, they cause no additional large contributions to $\Delta\rho$. ETC dynamics at a scale $M \gg 1$TeV generates the light fermion masses and contributes about a GeV to the heavy fermions' masses; this does not generate large corrections to $R_b$. The top condensate can, then, provide the bulk of the top quark mass. Precision electroweak data constrain the mass of the extra $Z$ boson in these models to weigh at least 1-2 TeV [20].

## Light Top Squarks

Finally, we return to supersymmetric models. Consider the mass matrix for the supersymmetric partners of the top quark:

$$\tilde{m}_t^2 = \begin{pmatrix} \begin{array}{c} \tilde{M}_Q^2 + m_t^2 \\ +M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta \end{array} & m_t(A_t + \mu\cot\beta) \\ & \\ m_t(A_t + \mu\cot\beta) & \begin{array}{c} \tilde{M}_U^2 + m_t^2 \\ +\frac{2}{3}M_Z^2\sin^2\theta_W\cos 2\beta \end{array} \end{pmatrix}$$

the presence of $m_t$ in the off-diagonal entries shows that a large top quark mass can drive one of the top squarks to be quite light. If the top squark is light enough (which experiment allows [21]) the decay $t \to \tilde{t}\tilde{N}$ becomes possible; that is, the top quark may be the only quark able to decay to its own superpartner.

This idea can be tested in top quark production experiments. The simplest test is to see whether the measured top mass and cross-section match, since the latter depends on how the top is assumed to decay. CDF and DO data indicate that assuming the top decays only through the standard channel $t \to Wb$ gives a good fit to the data [22]. If additional decay channels for the top existed, the production cross-section measured in the $WbWb$ final states would be lower than the standard model prediction. However, this effect could be balanced [23] in supersymmetric models either by production of states that decay to top quarks ($\tilde{g} \to t\tilde{t}$) or by production of states whose decays mimic those of top quarks ($\tilde{t} \to b\tilde{C}$). Checking these possibilities would require seeking, specific signatures of the presence of supersymmetric particles; for instance, while QCD produces mainly top anti-top pairs, gluino pair production with subsequent decay to top quarks and squarks also produces top/top and anti-top/anti-top pairs in the ratio $[t\bar{t} : tt : \overline{tt} \approx 2 : 1 : 1]$.

## CONCLUSIONS

The top quark's large mass singles it out in several ways. It may play a special role in electroweak symmetry breaking (through its effects on RG running in supersymmetric models or through formation of top quark condensates). It has potentially large effects on precision electroweak observables like $\Delta\rho$ or $R_b$. In some cases it has a strong influence on the masses of other particles such as higgs bosons or superpartners. Finally, the top quark may be subject to non-standard interactions that distinguish it from the up and charm quarks.

As a result, the top quark has already made a difference in our attempts to understand electroweak and flavor physics. Is the top quark actually different in any of the ways outlined here ? Time and experiment will tell!

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