The Atelistic Standard Model

Pierre Ramond

Institute for Fundamental Theory
Department of Physics
University of Florida

The Value of Schemes in Scientific Theory

Murray Gell-Mann

(Mendele'ev Centennial, 1969)

Preliminary Schemes:

- The perception of apparent patterns in the data

- The arrangement of facts into provisional structures

- The construction of phenomenological theories or rules

Guided mainly by the data and not by deep reasoning from theoretical principles or from underlying dynamical arguments. It is important to construct a scheme that has genuine predictive power.

- Mendele'ev Scheme in a very quantitative science; very long time lag until quantum mechanics.

- Darwin's Scheme in a science that at the time was mainly qualitative; two decades before the primary mechanism was elucidated.

Enormous prestige attaches today to sophisticated constructs as dynamical models, ... or theories employing fancy mathematics (often much fancier than the facts or the insights in the particular field would support).

Much less prestige adheres to the model phenomenological advances. This I think is a mistake. We should encourage ourselves, our friends, and younger colleagues to think in terms of seizing this kind of opportunity at times when the general dynamical synthesis in the Newtonian manner is not so easy to accomplish.

The Standard Model is an Unfinished Masterpiece

No Theory of Yukawa Couplings

Masses and mixings of the three families of chiral fermions in (3×3) Yukawa matrices $Y^{(a)}$, one for each electric charge $a = 2/3, -1/3, -1, 0$.

Quark and charged lepton masses and mixings break the electroweak symmetry ($\Delta I_w = 1/2$).

Tiny neutrino masses suggest a mixture of electroweak breaking and new ($\Delta I_w = 0$) physics sectors.

Lepton mixings yield two large crystalline mixing parameters, discordant with the "small" quark mixings

Standard Model without Yukawa Couplings displays global flavor symmetries with triplet representations

Perturbative SM's three gauge couplings at the electroweak scale, allow a theoretical peak (GQW's "desert") all the way to cosmology.

Unified gauge structures with chiral fermions

$$SU(3) \longrightarrow SU(3)\times SU(2)\times U(1) \longrightarrow SU(5) \longrightarrow SO(10) \longrightarrow E_6$$

Some keep them in their thoughts and wishes

Standard Model's Yukawa parameters may originate from (spontaneous) symmetry breaking of gauge and flavor symmetries, modeled with gauge-singlet bosons called "familons" (flavons).

"Familon physics" could be a portal to dark matter, or even dark matter itself should it contains a FAMP.

Largest flavor couplings to the heaviest quark may bode well for LHC, the best top quark factory in the planet.

Superstring Theory Explains Almost Everything

- Eleven or Ten Dimensional Nascent Universe
- "Superstring Compactification" to four dimensions
- Seven or six dimensional Euclidean Coset manifold
- E_6 Grand-Unified group

$$E_6 \longrightarrow SO(10) \longrightarrow SU(5) \longrightarrow SU(3)\times SU(2)\times U(1) \longrightarrow SU(3)$$

- Gauge Chiral Descent
- Topological number of massless chiral fermions

$$\sigma\cdot\mathcal{D}\Psi = (\sigma\cdot\mathcal{D})_{Mink} + (\sigma\cdot\mathcal{D})_{Coset}\Psi = (\sigma\cdot\mathcal{D})_{Coset}\Psi = 0$$

Flavors originate in the String Coset Manifold

Crazy Ideas

“Compactification” as a first order phase transition?

As nascent universe cools, seven or six dimensions binds in some way, creating frozen “dimensional ice crystals”.

Latent heat released to three space dimensions until all extra dimensions are frozen. Inflation?

“Dimensional crystals” could be related to the discrete groups acting on the coset manifold.

Tools for an effective theory of Yukawa couplings

- Textures: Yukawa Matrices, perceived patterns, scale?
- Grand-Unified Inputs
- Flavor Group

Textures

Textures specify input parameters of Yukawa matrices.

Matrix elements are designed to reproduce the CKM quark mixing matrix, and their masses, as well as the charged lepton masses (massless neutrinos).

Massive neutrinos: new parameters for the PMNS lepton mixing matrix constrained by oscillations, and neutrino masses.

Mass ordering as well as the CP-violating angle will "soon" be determined, where "soon" means soon.

$SU(5)$-inspired Textures

In $SU(5) \supset SU(2) \times SU(3)^c \times U(1)$ the chiral fermions live in two representations for each of the three families:

$$F: \quad \bar{\mathbf{5}} = (\mathbf{2}, \mathbf{1^c}) + (\mathbf{1}, \bar{\mathbf{3}}^\mathbf{c}) = \begin{pmatrix} \nu_e \\ e \end{pmatrix} + \bar{d}$$

$$T: \quad \mathbf{10} = (\mathbf{2}, \mathbf{3^c}) + (\mathbf{1}, \bar{\mathbf{3}}^\mathbf{c}) + (\mathbf{1}, \mathbf{1^c}) = \begin{pmatrix} u \\ d \end{pmatrix} + \bar{u} + \bar{e}$$

"Up" quark masses : $\quad T\,T = \mathbf{10}\times\mathbf{10} = \bar{\mathbf{5}} + \mathbf{50} + \mathbf{45} \supset \bar{u}\,u$

"Down" quark and charged lepton masses : $\quad F\,T = \bar{5}\times\mathbf{10} = \mathbf{5}+\mathbf{45} \supset \bar{d}\,d + e\,\bar{e}$

transposes of one another.

Georgi-Jarlskog $SU(5)$ Texture (1979):

Symmetric Yukawa matrices from Higgs along **5** and **45**

$$Y^{(u)} \sim \begin{pmatrix} 0 & \sqrt{m_u m_c} & 0 \\ \sqrt{m_u m_c} & 0 & \sqrt{m_c m_t} \\ 0 & \sqrt{m_c m_t} & m_t \end{pmatrix}$$

$$Y^{(d)} \sim \begin{pmatrix} 0 & \sqrt{m_d m_s} & 0 \\ \sqrt{m_d m_s} & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}; \qquad Y^{(e)} \sim \begin{pmatrix} 0 & \sqrt{m_d m_s} & 0 \\ \sqrt{m_d m_s} & -3m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

All from **5** Higgs, except 22 element from **45** Higgs different by -3.

$$Y^{(d)} = \mathcal{U}_{CKM} \mathrm{Diag}(m_b, m_s, m_d) \mathcal{V}_{(d)}; \qquad Y^{(e)} = \mathcal{U}_{(e)} \mathrm{Diag}(m_\tau, m_\mu, m_e) \mathcal{V}_{(e)}$$

$$m_\tau = m_b, \quad m_\mu = 3m_s, \quad m_e = m_d/3 \quad \longrightarrow \quad \frac{m_e}{m_\mu} = \frac{m_d}{9m_s}$$

Quark mass values at $SU(5)$ breaking scale

$$m_b(10\ GeV) = \frac{1}{2} M_\Upsilon \quad \longrightarrow \quad m_b(10^{15}\ GeV) \approx m_\tau$$

$\mathcal{U}_{CKM}$ and $\mathcal{U}_{(e)}$ contain only small angles

Expand GJ texture to three right-handed neutrinos $\bar{N}$

Lepton mixing matrix is now observable, with $U_{(\nu)}$ to diagonalize neutrino masses

$$\mathcal{U}_{PMNS} = \mathcal{U}^{\dagger}_{(e)}\mathcal{U}_{(\nu)}$$

Approximate large atmospheric and solar oscillations angles by the TriBiMaximal (TBM) matrix

$$U_{(\nu)} \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \equiv \mathcal{U}_{TBM}$$

"Reactor angle" generated only from $\mathcal{U}_{(e)}$ yields half the experimental value.

Too little "Cabibbo haze" with Symmetric Yukawas

Symmetric Yukawas: TBM approximation fails

Oxford Texture (2018):

$SU(5)$-inspired Texture with symmetric Yukawas with different neutrino mixing:

$$Y^{(a)} = \begin{pmatrix} 0 & \epsilon_a^3 & \epsilon_a^3 \\ \epsilon_a^3 & r_a\epsilon_a^2 & r_a\epsilon_a^2 \\ \epsilon_a^3 & r_a\epsilon_a^2 & 1 \end{pmatrix}$$

$$r_{u,d} = 1/3, \quad r_e = -1, \qquad \epsilon_u = .05, \quad \epsilon_{d,e} = 0.15$$

Asymmetric Florida Texture

Yukawas that yield the same $SU(5)$ relations with $\mathcal{O}(\lambda)$ asymmetry:

$$Y^{(d)} = \begin{pmatrix} bd\lambda^4 & a\lambda^3 & b\lambda^3 \\ a\lambda^3 & c\lambda^2 & g\lambda^2 \\ d\lambda & g\lambda^2 & 1 \end{pmatrix} \quad Y^{(e)} = \begin{pmatrix} bd\lambda^4 & a\lambda^3 & d\lambda \\ a\lambda^3 & -3c\lambda^2 & g\lambda^2 \\ b\lambda^3 & g\lambda^2 & 1 \end{pmatrix}$$

$a = c = \frac{1}{3}$, $g = A$, $b = A\sqrt{\rho^2 + \eta^2}$, $d = \frac{2}{3A}$

$\mathcal{U}_{(e)}$ with asymmetry of $\mathcal{O}(\lambda)$: too much Cabibbo haze!

With TBM mixing:

θ_{13} is 2.26° **above** pdg;

θ_{12} is 6.16° above pdg; θ_{23} is 2.90° below pdg

TBM with phase δ lowers the reactor angle:

θ_{13} set at pdg $\longrightarrow$ $\delta = \pm 78^\circ : \delta_{CP} = \pm 1.32\pi$;

θ_{12} is 0.51° above pdg; θ_{23} is 0.66° below pdg

CP phase predicted up to a sign

TBM works for Yukawas with $\mathcal{O}(\lambda)$ asymmetry

Flavor Groups

Three chiral families of quarks and leptons suggest continuous flavor groups $SO(3)$ and $SU(3)$, with real and complex triplets, respectively.

These continuous flavor groups only distinguish symmetric from antisymmetric matrices without specifying their matrix elements

Kronecker product for triplets:

$$SO(3): \quad \mathbf{3}\times\mathbf{3} = (\mathbf{1}+\mathbf{5})_s+\mathbf{3}_a; \quad SU(3): \quad \mathbf{3}\times\mathbf{3} = \mathbf{6}_s+\mathbf{3}_a$$

Infinite number of discrete non-Abelian subgroups of $SO(3)$ and $SU(3)$ with triplet representations.

Two types: those with the same triplet-triplet Kronecker products as their continuous progenitor; others yield more information on the Yukawa's matrix elements.

Nature's parsimony: limit analysis to lowest order subgroups

$SO(3)$ subgroups

- $\mathcal{A}_4$ of order 12 with one triplet

$$\mathbf{3} \times \mathbf{3} = (\mathbf{1} + \mathbf{1}' + \bar{\mathbf{1}}' + \mathbf{3})_s + \mathbf{3}_a$$

- $\mathcal{S}_4$ of order 24 with two triplets $\mathbf{3_{1,2}}$

$$\mathbf{3_1} \times \mathbf{3_1} = (\mathbf{1} + \mathbf{2} + \mathbf{3_1})_s + \mathbf{3_2}_a; \quad \mathbf{3_2} \times \mathbf{3_2} = (\mathbf{1} + \mathbf{2} + \mathbf{3_2})_s + \mathbf{3_1}_a$$

-$\mathcal{A}_4' = \mathcal{T}'$ double cover of order 24

$$\mathbf{3} \times \mathbf{3} = (\mathbf{1} + \mathbf{1}' + \bar{\mathbf{1}}' + \mathbf{3})_s + \mathbf{3}_a$$

-$\mathcal{A}_5$ of order 60 with two real triplets $\mathbf{3_{1,2}}$

$$\mathbf{3_1} \times \mathbf{3_1} = (\mathbf{1} + \mathbf{5})_s + \mathbf{3_1}_a; \quad \mathbf{3_2} \times \mathbf{3_2} = (\mathbf{1} + \mathbf{5})_s + \mathbf{3_2}_a$$

-$\mathcal{A}_5'$ double cover of order 120

$$\mathbf{3_1} \times \mathbf{3_1} = (\mathbf{1} + \mathbf{5})_s + \mathbf{3_1}_a$$

Discrete $SU(3)$ subgroups with triplet Irreps:

$$\mathcal{T}_7 = \mathcal{Z}_7 \rtimes \mathcal{Z}_3; \quad \Delta(27) = (\mathcal{Z}_3 \times \mathcal{Z}_3) \rtimes \mathcal{Z}_3,$$

$$\mathcal{T}_{13} = \mathcal{Z}_{13} \rtimes \mathcal{Z}_3; \quad \Delta(48) = (\mathcal{Z}_4 \times \mathcal{Z}_4) \rtimes \mathcal{Z}_3$$

$\mathcal{T}_7$'s finite progenitor is the simple $\mathcal{PSL}_2(7)$ of order 168, which itself contains a complex triplet.

$\mathcal{T}_{13}$'s progenitor, the simple group of order 1092, $\mathcal{PSL}_2(13)$ without complex triplet.

Noteworthy: $\mathcal{PSL}_2(7)$ has a six and seven dimensional representation, while and $\mathcal{PSL}_2(13)$'s lowest representations are both seven-dimensional. Both progenitors are finite subgroups of continuous G_2.

$\mathcal{Z}_7 \rtimes \mathcal{Z}_3$

Irreps: three singlets $\mathbf{1}$, $\mathbf{1}'$, $\overline{\mathbf{1}}'$, one complex triplet $\mathbf{3}$

$$\mathbf{3} \times \mathbf{3} = (\mathbf{3} + \overline{\mathbf{3}})_{\mathbf{s}} + \overline{\mathbf{3}}_{\mathbf{a}}, \quad \mathbf{3} \times \overline{\mathbf{3}} = \mathbf{1} + \mathbf{1}' + \overline{\mathbf{1}}' + \mathbf{3} + \overline{\mathbf{3}}$$

$\Delta(27) = (\mathcal{Z}_3 \times \mathcal{Z}_3) \rtimes \mathcal{Z}_3$

Irreps: nine singlets: $\mathbf{1}_{r,s}; r, s = 0, 1, 2,$ and one complex triplet $\mathbf{3}$

$$\mathbf{3} \times \mathbf{3} = (\overline{\mathbf{3}} + \overline{\mathbf{3}})_{\mathbf{s}} + \overline{\mathbf{3}}_{\mathbf{a}}, \qquad \mathbf{3} \times \overline{\mathbf{3}} = \sum_{\mathbf{r},\mathbf{s}=\mathbf{0},\mathbf{1},\mathbf{2}} \mathbf{1}_{\mathbf{r},\mathbf{s}}$$

$\mathcal{Z}_{13} \rtimes \mathcal{Z}_3$

Irreps: one real and one complex singlet $\mathbf{1}, \mathbf{1}'$, two complex triplets $\mathbf{3_1}$, $\mathbf{3_2}$

$$\mathbf{3_1}\times\mathbf{3_1} = \mathbf{3_{2s}}+\overline{\mathbf{3}}_{\mathbf{1s}}+\overline{\mathbf{3}}_{\mathbf{1a}}, \quad \mathbf{3_2}\times\mathbf{3_2} = \overline{\mathbf{3}}_{\mathbf{1}}+\overline{\mathbf{3}}_{\mathbf{2s}}+\overline{\mathbf{3}}_{\mathbf{2a}}, \quad \mathbf{3_1}\times\mathbf{3_2} = \mathbf{3_1}+\overline{\mathbf{3}}_{\mathbf{2}}+\mathbf{3_2}$$

$\Delta(48) = (\mathcal{Z}_4 \times \mathcal{Z}_4) \rtimes \mathcal{Z}_3$

Irreps: one real, one complex singlet 1, $\mathbf{1}'$, one real triplet $\mathbf{3_0}$, and two complex

$$\mathbf{3_1}\times\mathbf{3_1} = (\mathbf{3_0}+\overline{\mathbf{3}}_{\mathbf{1}})_{\mathbf{s}}+\overline{\mathbf{3}}_{\mathbf{1a}}, \quad \mathbf{3_2}\times\mathbf{3_2} = (\mathbf{3_0}+\overline{\mathbf{3}}_{\mathbf{1}})_{\mathbf{s}}+\overline{\mathbf{3}}_{\mathbf{2\,a}} \quad \mathbf{3_1}\times\mathbf{3_2} = \mathbf{3_0}+\overline{\mathbf{3}}_{\mathbf{1}}+\mathbf{3_2}$$

Diagonal Matrix: $\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}$

Hollow Matrix: $\begin{pmatrix} & * & * \\ * & & * \\ * & * & \end{pmatrix}$

Chiral Fermions of Interest:

$$SU(5) \qquad \underset{F}{\bar{\mathbf{5}}} + \underset{T}{\mathbf{10}}$$

$$SO(10) \qquad \mathbf{16} = \underset{F}{\bar{\mathbf{5}}} + \underset{T}{\mathbf{10}} + \underset{\bar{N}}{\mathbf{1}}$$

$$E_6 \qquad \mathbf{27} = \mathbf{16} + \mathbf{10_v} + \mathbf{1} = (\underset{F}{\bar{5}} + \underset{T}{10} + \underset{\bar{N}}{1}) + (\underset{F'}{5} + \underset{\bar{F}'}{\bar{5}}) + \underset{\bar{N}'}{1}$$

Majorana Matrices

Three right-handed neutrinos $\bar{N}$ at $SO(10)$ level.

- $\bar{N} \sim \ \Delta(27)$ triplet $: \bar{N}\bar{N} \sim (\mathbf{3} \times \mathbf{3})_{\mathbf{s}} = \bar{\mathbf{3}} + \bar{\mathbf{3}}$

Diagonal *and* Hollow matrices: $\begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}_{\bar{\mathbf{3}}+\bar{\mathbf{3}}}$

- $\bar{N} \sim \mathcal{T}_7$ triplet $: \bar{N}\bar{N} \sim (\mathbf{3} \times \mathbf{3})_{\mathbf{s}} = \mathbf{3} + \bar{\mathbf{3}}$

$$\begin{pmatrix} * & & \\ & * & \\ & & * \end{pmatrix}_{\bar{3}} + \begin{pmatrix} & * & * \\ * & & * \\ * & * & \end{pmatrix}_{\mathbf{3}}$$

Distinguishes diagonal from off-diagonal elements

(Same Structure for $\mathcal{T}_{13}$ and $\Delta(48)$)

Diagonal Coupling with familon $\Phi \sim \ \bar{\mathbf{3}} = (\varphi_1,\, \varphi_2,\, \varphi_3)$:

$$N^t \begin{pmatrix} \varphi_3 & 0 & 0 \\ 0 & \varphi_2 & 0 \\ 0 & 0 & \varphi_1 \end{pmatrix} N$$

Hollow Coupling with familon $\Phi' \sim \mathbf{3} = (\varphi'_1, \varphi'_2, \varphi'_3)$

$$N_1 N_2 \varphi'_2 + N_2 N_3 \varphi'_3 + N_2 N_3 \varphi'_1; \qquad N^t \begin{pmatrix} 0 & \varphi'_2 & \varphi'_3 \\ \varphi'_2 & 0 & \varphi'_1 \\ \varphi'_3 & \varphi'_1 & 0 \end{pmatrix} N \equiv N^t H N$$

$$H \equiv \mathcal{C}\mathcal{G}\mathcal{C}^T$$

$$\mathcal{C} = \sqrt{\varphi_1 \varphi_2 \varphi_3} \begin{pmatrix} \varphi_1^{-1} & 0 & 0 \\ 0 & \varphi_3^{-1} & 0 \\ 0 & 0 & -\varphi_2^{-1} \end{pmatrix}$$

$$\mathcal{G} = \begin{pmatrix} 0 & 1 & -1 \\ 1 & 0 & -1 \\ -1 & -1 & 0 \end{pmatrix}$$

Diagonalized by TriBiMaximal!

$$\mathcal{G} = \mathcal{U}_{TBM} Diag(-1, 2, -1) \mathcal{U}^t_{TBM}$$

$$\mathcal{P}\mathcal{G}\mathcal{P}^t = \mathcal{G}, \quad \mathcal{P} \text{ permutation}$$

Good News/Bad News

Seesaw TBM

Seesaw with $\bar{N}$ triplet : unphysical neutrino masses:

$$m_{\nu_2} = \frac{1}{2} m_{\nu_3}, \quad m_{\nu_1} = 2 m_{\nu_2}, \quad m_{\nu_1} = m_{\nu_3}$$

$$\mathcal{ZUT} \longrightarrow \text{Six Right} - \text{handed Neutrinos}$$

$$(6 \times 6) \text{ Majorana Matrix} \quad \begin{pmatrix} \mathcal{M}_{00} & \mathcal{M}_{01} \\ \mathcal{M}_{10}^t & \mathcal{M}_{11} \end{pmatrix}$$

$$\mathcal{ZOT}\ \mathcal{ZOT}$$