The Standard Model and Beyond

- The standard model
- Testing the standard model
- Problems
- Beyond the standard model
- Where are we going?

Yoichiro Nambu Symposium (April 21, 2005)  Paul Langacker (Penn)
The New Standard Model

- Standard model, supplemented with neutrino mass (Dirac or Majorana):

  \[ SU(3) \times SU(2) \times U(1) \times \text{classical relativity} \]

- Mathematically consistent field theory of strong, weak, electromagnetic interactions

- Correct to first approximation down to \(10^{-16}\) cm

- Complicated, free parameters, fine tunings \(\Rightarrow\) must be new physics
### The Fundamental Forces

<table>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>$\pi^0$</td>
<td>e$^-$</td>
<td>$W^-$</td>
</tr>
<tr>
<td>p</td>
<td>pion</td>
<td>$\gamma$</td>
<td>$e^-$</td>
</tr>
<tr>
<td>d</td>
<td>gluon</td>
<td>photon</td>
<td>n</td>
</tr>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **$V = g_\pi^2 e^{-m_{\pi}r}$**
- **$\frac{e^2}{r}$**
- **$g^2 e^{-M_{W}r}$**
- **$G_N \frac{m_1 m_2}{r}$**

- **Strength:** $\frac{g_\pi^2}{4\pi} \approx 14$
- **$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$**
- **$\frac{g^2 E^2}{M_{W}^2} \approx 10^{-11}$**
- **$G_N m_1 m_2 \approx 10^{-38}$**
  - $(m_1 = m_2 = 1$ GeV$)$

- **Range:**
  - $\frac{\hbar}{m_{\pi}c} \approx 10^{-13}$ cm $\equiv 1$ fm
  - $\frac{\hbar}{M_{W}c} \approx 10^{-16}$ cm
  - $\infty$

---

*Yoichiro Nambu Symposium (April 21, 2005)*

Paul Langacker (Penn)
## Unification of Forces

<table>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>hadrons:</strong> $p, n; \pi^\pm, \pi^0$; pions: $\pi^\pm, \pi^0$; (QCD: quarks, gluons)</td>
<td>charged particles: $e^-, \mu^-, \tau^-$; $p; \pi^\pm$</td>
<td>$p, n, \pi; e, \mu, \tau$; neutrinos: $\nu_e, \nu_\mu, \nu_\tau$</td>
<td>all particles (always attractive)</td>
</tr>
</tbody>
</table>

$\leftarrow E + B \rightarrow$ (Maxwell)

$\leftarrow$ QCD $\rightarrow$ $\leftarrow$ Electroweak $(SU(2) \times U(1)) \rightarrow$

$\leftarrow$ Grand Unification (GUT)? $\rightarrow$

$\leftarrow$ Theory of Everything (superstring)? $\rightarrow$
Gauge Theories

- Gauge symmetry requires existence of (apparently) massless spin-1 (vector, gauge) bosons
- Interactions prescribed up to group, representations, gauge coupling
- Analogous to QED ($U(1)$), but gauge self interactions for non-abelian groups
- Standard model: $SU(3) \times SU(2) \times U(1)$
- Application to strong (short range) $\Rightarrow$ confinement
- Application to weak (short range) $\Rightarrow$ spontaneous symmetry breaking (Higgs or dynamical)
- Unique renormalizable field theory for spin-1
The Standard Model

- **Gauge group** \( SU(3) \times SU(2) \times U(1); \) gauge couplings \( g_s, g, g' \)

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}_L \begin{pmatrix}
  u \\
  d
\end{pmatrix}_L \begin{pmatrix}
  u \\
  d
\end{pmatrix}_L \begin{pmatrix}
  \nu_e \\
  e^-
\end{pmatrix}_L
\]

\[
\begin{array}{cccc}
u_e & u_R & u_R & \nu_{eR}(?) \\
d_R & d_R & d_R & e_R^-
\end{array}
\]

( \( L \) = left-handed, \( R \) = right-handed)

- **SU(3):** \( u \leftrightarrow u \leftrightarrow u, \ d \leftrightarrow d \leftrightarrow d \) (gluons)

- **SU(2):** \( u_L \leftrightarrow d_L, \ \nu_{eL} \leftrightarrow e_L^- \) (\( W^\pm \)); phases (\( W^0 \))

- **U(1):** phases (\( B \))

- **Heavy families** \((c, s, \nu_\mu, \mu^-), \ (t, b, \nu_\tau, \tau^-)\)
Quantum Chromodynamics (QCD)

Modern theory of the strong interactions

- Quark model/ color/ confinement
- Low energy symmetries (+ realization, breaking) ($SU(3)_L \times SU(3)_R$)
- Hadronic models: Yukawa, Regge, dual resonance ($\rightarrow$ strings)
- Asymptotic freedom (weak coupling at high energy)
Yoichiro Nambu Symposium (April 21, 2005)

Paul Langacker (Penn)
Relation of “running” $\alpha_s$ at different scales

Yoichiro Nambu Symposium (April 21, 2005)  Paul Langacker (Penn)
## Quantum Electrodynamics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value of $\alpha^{-1}$</th>
<th>Difference from $\alpha^{-1}(a_e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviation from gyromagnetic ratio, $a_e = (g - 2)/2$ for $e^-$</td>
<td>137.035 999 58 (52)</td>
<td>$[3.8 \times 10^{-9}]$</td>
</tr>
<tr>
<td>ac Josephson effect</td>
<td>137.035 988 0 (51)</td>
<td>$[3.7 \times 10^{-8}]$</td>
</tr>
<tr>
<td>$h/m_n$ ($m_n$ is the neutron mass) from $n$ beam</td>
<td>137.036 011 9 (51)</td>
<td>$[3.7 \times 10^{-8}]$</td>
</tr>
<tr>
<td>Hyperfine structure in muonium, $\mu^+e^-$</td>
<td>137.035 993 2 (83)</td>
<td>$[6.0 \times 10^{-8}]$</td>
</tr>
<tr>
<td>Cesium $D_1$ line</td>
<td>137.035 992 4 (41)</td>
<td>$[3.0 \times 10^{-8}]$</td>
</tr>
</tbody>
</table>
Neutrinos Implications/questions

• Key constituent of the Universe
• Why are the masses so small?
  – Planck/GUT scale? e.g., seesaw mechanism,
  \( m_\nu \sim m_2 \text{D} / M_{\text{MN}} \)
• Are the neutrinos Dirac or Majorana?
  – Neutrinoless double-beta decay \( w_{\beta\beta} \) inverted or degenerate spectrum

Yoichiro Nambu Symposium (April 21, 2005) Paul Langacker (Penn)
Neutrinos Implications/questions
• Key constituent of the Universe
• Why are the masses so small?
  – Planck/GUT scale? e.g.,

\[ \omega \nu \sim \frac{m^2}{M_N} \]

- Neutrino double beta decay

\[ w^{\beta\beta} \nu_y \] inverted or degenerate

spectrally

Yoichiro Nambu Symposium (April 21, 2005)
Paul Langacker (Penn)
Neutrinos Implications/questions

- Key constituent of the Universe
- Why are the masses so small?
  - Planck/GUT scale?... etc.
  - Generalization, $\nu \propto m^2_D / M_N$

- Are the neutrinos Dirac or Majorana?
  - Neutrinoless double beta decay

$\beta \beta^0 \nu y \ \text{winverted or degenerate}$

Yoichiro Nambu Symposium (April 21, 2005)
Paul Langacker (Penn)
• SM correct and unique to zeroth approx. (gauge principle, group, representations)

• SM correct at loop level (renorm gauge theory; $m_t, \alpha_s, M_H$)

• TeV physics severely constrained (unification vs compositeness)

• Precise gauge couplings (gauge unification)
Heavy $B$ decays and $CP$ violation
  - CKM (quark mixing) description of $CP$ breaking
  - Unitarity triangle
  - Search for new physics
  - Baryogenesis?

---

Yoichiro Nambu Symposium (April 21, 2005)
Paul Langacker (Penn)
Problems with the Standard Model

Lagrangian after symmetry breaking:

\[ \mathcal{L} = L_{\text{gauge}} + L_{\text{Higgs}} + \sum_i \bar{\psi}_i \left( i \dot{\varphi} - m_i - \frac{m_i H}{\nu} \right) \psi_i \]

\[ -\frac{g}{2\sqrt{2}} \left( J_\mu^W W^-_\mu + J_\mu^\dagger W^+_\mu \right) - e J_Q^\mu A_\mu - \frac{g}{2 \cos \theta_W} J_Z^\mu Z_\mu \]

Standard model: \( SU(2) \times U(1) \) (extended to include \( \nu \) masses) + QCD + general relativity

Mathematically consistent, renormalizable theory

Correct to \( 10^{-16} \) cm
However, too much arbitrariness and fine-tuning: $O(27)$ parameters (+ 2 for Majorana $\nu$), and electric charges

- **Gauge Problem**
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)

- **Fermion problem**
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature? Probe of Planck/GUT scale?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.
• Higgs/hierarchy problem
  - Expect $M_H^2 = O(M_W^2)$
  - higher order corrections:
    $\delta M_H^2 / M_W^2 \sim 10^{34}$

Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs; anthropically motivated fine-tuning (split supersymmetry) (landscape)

• Strong CP problem
  - Can add $\frac{\theta}{32\pi^2} g_s^2 F \tilde{F}$ to QCD (breaks, P, T, CP)
  - $d_N \Rightarrow \theta < 10^{-9}$, but $\delta \theta |_{\text{weak}} \sim 10^{-3}$
  - Possible solutions: spontaneously broken global $U(1)$ (Peccei-Quinn) $\Rightarrow$ axion; unbroken global $U(1)$ (massless $u$ quark); spontaneously broken CP + other symmetries
Graviton problem

- gravity not unified
- quantum gravity not renormalizable
- cosmological constant: \( \Lambda_{SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\text{obs}} \) (10^{124} for GUTs, strings)
- Possible solutions:
  * supergravity and Kaluza Klein unify
  * strings yield finite gravity.
  * \( \Lambda \)? Anthropically motivated fine-tuning (landscape)?
Beyond the Standard Model

- The Whimper: A new layer at the TeV scale
- The Hybrid: low fundamental scale/large extra dimensions
- The Bang: unification at the Planck scale, $M_P = G_N^{-1/2} \sim 10^{19}$ GeV
Compositeness

- Onion-like layers
- Composite fermions, scalars (dynamical sym. breaking)
- \textit{Not like to atom} $\rightarrow$ nucleus $+ e^- \rightarrow p + n \rightarrow \text{quark}$
- At most one more layer accessible (Tevatron, LHC, ILC)
- Rare decays (e.g., $K \rightarrow \mu e$)
- Effects (typically, few \%) expected at LEP/SLC, WNC
- anomalous $VVV$, new particles, future $WW \rightarrow WW$, FCNC, EDM
- Recent variant: Little Higgs
Large extra dimensions (deconstruction, brane worlds)

- Can be motivated by strings, but new dimensions much larger than $M_P^{-1} \sim 10^{-33} \text{ cm}$

- Fundamental scale $M_F \sim 1 - 100 \text{ TeV} \ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18} \text{ GeV}$
  
  - Assume $\delta$ extra dimensions with volume $V_{\delta} \gg M_F^{-\delta}$

  \[
  \bar{M}_{Pl}^2 = M_F^{2+\delta} V_{\delta} \gg M_F^2
  \]

  (Introduces new hierarchy problem)
- Black holes, graviton emission at colliders!
- Macroscopic gravity effects
- Astrophysics

Yoichiro Nambu Symposium (April 21, 2005)

Paul Langacker (Penn)
Unification

- Unification of interactions
- Grand desert to unification (GUT) or Planck scale
- Elementary Higgs, supersymmetry (SUSY), GUTs, strings
- Possibility of probing to $M_P$ and very early universe
Supersymmetry

- Fermion ↔ boson symmetry

- Motivations
  - stabilize weak scale ⇒ $M_{SUSY} < \mathcal{O}(1 \text{ TeV})$
  - supergravity (gauged supersymmetry): unification of gravity (non-renormalizable)
  - coupling constants in supersymmetric grand unification
  - decoupling of heavy particles (precision)
• Consequences

- additional charged and neutral Higgs particles

- $M_{H^0}^2 < \cos^2 2\beta M_Z^2 + \text{H.O.T.} (O(m_t^4)) < (150 \text{ GeV})^2$, consistent with LEP

* cf., standard model: $M_{H^0} < 1000 \text{ GeV}$
• Superpartners
  - $q \Rightarrow \tilde{q}$, scalar quark
  - $\ell \Rightarrow \tilde{\ell}$, scalar lepton
  - $W \Rightarrow \tilde{w}$, wino
  - typical scale: several hundred GeV
  - LSP: cold dark matter candidate
  - SUSY breaking $\Leftrightarrow$ large $m_t$
  - May be large FCNC, EDM, $\Delta(g_\mu - 2)$

\[ \mathcal{L}_d = \frac{d}{2} \psi \gamma_5 \sigma_{\mu \nu} \psi F_{\mu \nu} \]
Grand Unification

- Unify strong $SU(3)$ and electroweak $SU(2) \times U(1)$ in simple group, broken at $\sim 10^{16}$ GeV
- Gauge unification (only in supersymmetric version)

\[ \alpha_i \]

\[ \alpha_s(M_Z) = 0.117 \pm 0.005 \]

\[ \sin^2 \theta_{\text{MS}} = 0.2317 \pm 0.0004 \]

Yoichiro Nambu Symposium (April 21, 2005)  
Paul Langacker (Penn)
• Seesaw model for small $m_{
u}$ (but why are mixings large?)

• Quark-lepton ($q - l$) unification ($\Rightarrow$ charge quantization)

• $q - l$ mass relations (work only for third family in simplest versions)

• Proton decay? (simplest versions excluded)

• Doublet-triplet problem?

• String embedding? (breaking, families may be entangled in extra dimensions)
Superstrings

- Finite, “parameter-free” “theory of everything” (TOE), including quantum gravity
  - 1-d string-like object
  - Appears pointlike for resolution $> M_P^{-1} \sim 10^{-33}$ cm
  - Vibrational modes $\rightarrow$ particles
  - Consistent in 10 space-time dimensions $\rightarrow$ 6 must compactify to scale $M_P^{-1}$
  - 4-dim supersymmetric gauge theory below $M_P$
  - May also be solitons (branes), terminating open strings
• Problems
  – Which compactification manifold?
  – Supersymmetry breaking? Cosmological constant?
  – Many moduli (vacua). Landscape ideas - is there any predictability left?
  – Relation to supersymmetric standard model, GUT?

• Need theoretical progress and hints from experiment
  – TeV scale remnants, such as $Z'$, exotics
  – SUSY breaking patterns
  – Need very precise masses and couplings → International Linear Collider
Future/present Experiments

- High energy colliders: the primary tool
  - The TEVATRON; Fermilab, 1.96 TeV $\bar{p}p$, exploration
  - The Large Hadron Collider (LHC); CERN, 14 TeV $pp$, high luminosity, discovery (Discovery machine for supersymmetry, $R_p$ violation, string remnants (e.g., $Z'$, exotics); or compositeness, dynamical symmetry breaking, Higgless theories, Little Higgs, large extra dimensions, ...)
  - The International Linear Collider (ILC), in planning; 500 GeV-1 TeV $e^+e^-$, cold technology, high precision studies (Precision parameters to map back to string scale)

- Also, CP violation ($B$ decays, electric dipole moments), flavor changing neutral currents, neutrino physics
Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- **Particle Physics**
  - $\nu N, \mu N, eN$ scattering: existence/properties of quarks, QCD
  - Weak decays ($n \rightarrow pe^-\bar{\nu}_e, \mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$): Fermi theory, parity violation, mixing
  - Neutral current, $Z$-pole, atomic parity: electroweak unification, field theory, $m_t$; severe constraint on physics to TeV scale
  - Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions; seesaw: $m_\nu \sim m_q^2/M_{GUT}$
- Solar/atmospheric neutrino experiments
  - Neutrinos have tiny masses (but large mixings)
  - Standard Solar model confirmed
  - First oscillation dips observed! (QM on large scale)
• 3 ν Patterns
  
  – Solar: LMA (SNO, Kamland)
  
  – $\Delta m^2_{\odot} \sim (10^{-5} - 10^{-4})$ eV$^2$ for LMA
  
  – Atmospheric: $\Delta m^2_{\text{Atm}} \sim 3 \times 10^{-3}$ eV$^2$, near-maximal mixing
  
  – Reactor: $U_{e3}$ small

Yoichiro Nambu Symposium (April 21, 2005) Paul Langacker (Penn)
Neutrino Implications/questions

- Key constituent of the Universe
- Why are the masses so small?
  - Planck/GUT scale? e.g., seesaw or generalization, $m_\nu \sim m_D^2/M_N$
- Are the neutrinos Dirac or Majorana?
  - Neutrinoless double beta decay ($\beta\beta_{0\nu}$) (inverted or degenerate spectra)
• What is the spectrum: number, mass scale/pattern, mixings
  - Scale: $\beta$ decay (KATRIN), $\beta\beta_0\nu$, large scale structure (SDSS)
  - Mixings: reactor, long baseline oscillation experiments, Solar
  - Pattern: long baseline, $\beta\beta_0\nu$, supernova
  - Number: MiniBooNE

• Leptogenesis?

• Relic neutrinos?
  - Indirect: Nucleosynthesis, large scale structure. Direct? (Z-burst?)

Yoichiro Nambu Symposium (April 21, 2005)  
Paul Langacker (Penn)
The Universe

The concordance

- 5% matter (including dark baryons): CMB, BBN, Lyman $\alpha$
- 25% dark matter (galaxies, clusters, CMB, lensing)
- 70% dark energy (Acceleration (Supernovae), CMB (WMAP))

Yoichiro Nambu Symposium (April 21, 2005)  
Paul Langacker (Penn)
● What is the dark energy?

- Vacuum energy (cosmological constant); time varying field (quintessence)?
- High precision supernova survey (SNAP); CMB (Planck)
time varying couplings and parameters

\begin{align*}
H_0 &= 70 \text{ km s}^{-1}\text{Mpc}^{-1} \\
\Omega_M &= 0.3, \; \Omega_\Lambda = 0.7 \\
\rightarrow t_0 &= 13.46 \text{ Gyr}
\end{align*}

\begin{itemize}
\item Atomic clocks: Sortais et al. '01
\item Oklo: Fujii et al. '00
\item \(\beta\)-decay: Olive et al. '02
\item 21 ADs: Murphy et al. '01 [12]
\item 128 MMs: Present work
\end{itemize}

(Murphy et al, astro-ph/0209488)

Yoichiro Nambu Symposium (April 21, 2005)  Paul Langacker (Penn)
• What is the dark matter?

- Lightest neutralino in supersymmetry (if $R$ parity conserved)? Axion?
- Direct searches: LHC, ILC; cold dark matter searches; high energy annihilation $\nu$'s
- Axion searches (resonant cavities)
- Gravitation lensing (SNAP), CMB (Planck)
● Why is there matter and not antimatter?

- $n_B/n_\gamma \sim 10^{-10}$, $n_\bar{B} \sim 0$
- Electroweak baryogenesis? Leptogenesis? Decay of heavy fields? $CPT$ violation?

---

Yoichiro Nambu Symposium (April 21, 2005)  
Paul Langacker (Penn)
• The very beginning (inflation)
  – Relation to particle physics, strings, $\Lambda$?
  – CMB (Planck); gravity waves (LISA)
Conclusions

• The standard model is the correct description of nature down to
  \( \sim 10^{-16} \text{ cm} \sim \frac{1}{\text{ TeV}} \)

• Standard model is complicated \( \rightarrow \) must be new physics

• Precision tests severely constrain new TeV-scale physics

• Promising theoretical ideas at Planck scale

• Promising experimental program at colliders, accelerators, low
  energy, cosmology

• Challenge to make contact between theory and experiment