Where do we go from here?

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A cautionary tale
 cf. Observational Geography, c. 1953
Britain on top of the world on this Elizabeth II day

EVEREST IS CONQUERED

Queen awakened to hear of climbers’ triumph

2 REACH SUMMIT ON 11th EXPEDITION

THE QUEEN WAS WAKENED AT BUCKINGHAM PALACE LATE LAST NIGHT TO BE TOLD THAT THE BRITISH EXPEDITION HAS CONQUERED MOUNT EVEREST.

This great news, on the eve of the Coronation, reached London last night in a message to “The Times” from Col. John Hunt in charge of the expedition.

The climb was made on Friday and Col. Hunt has reported that “all is well.”

The successful assault was made by Mr. E. P. Hillary, a New Zealander, and the Sherpa porter named Tensing Bhutia.

This great feat of the new Elizabethans flashed round the world adding still further joy to the heightening Coronation fever.

Mr. Hillary, aged 34, is a bee-keeper in New Zealand. His climbing experience was gained in the Southern Alps of the South Island, a range that has attracted mountaineers from all over the world because of the difficulty of the climb.

New route

Mr. Hillary
He reached the summit.

1 a.m. AND ROYAL ROUTE BARRIERS ARE CLOSED

CROWD barriers were closed hours before schedule early this morning as tens of thousands of sightseers camped along the Coronation route.

Fifty thousand people hounded by 7,000 cars.

Duke will watch
1953 - The high energy frontier
1953 - The high energy frontier (of gravitational potential).
1953 - Where do we go from here?
Nowhere.
2013 - Where do we go from here?
2013 - The high energy frontier (of particle physics).
Where is ‘here’?
Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

\[-\frac{1}{2}\partial_\nu g^a_{\mu\rho} \partial_\rho g^a_{\mu\nu} - g_s f^{abc} \partial_\mu g^b_{\rho\nu} g^c_{\mu\rho} - \frac{1}{4} g_s f^{abc} f^{ade} g^b_{\rho\nu} g^e_{\mu\rho} g^d_{\mu\nu} + \frac{1}{2} i g_s^2 (g^2)^{\gamma}_{\mu\nu} g^a_{\mu\nu} + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a g^b_{\mu\nu} g^c_{\mu\nu} - \partial_\nu W^+_{\mu\nu} W^-_{\mu\nu} - M^2 W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{2} \partial_\nu Z^0_{\mu\nu} Z^0_{\mu\nu} - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{4} M \phi^0 \phi^0 - \beta_4 [\frac{2 M^2}{g^2} + 2 M H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-)] + \frac{2 M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z^0_{\mu\nu} (W^+_{\mu\nu} W^-_{\mu\nu} - W^+_{\mu\nu} W^-_{\mu\nu}) - Z^0_{\mu\nu} (W^+_{\mu\nu} \partial_\nu W^-_{\mu\nu} - W^-_{\mu\nu} \partial_\nu W^+_{\mu\nu}) + Z^0_{\mu\nu} (W^+_{\mu\nu} \partial_\nu W^-_{\mu\nu} - W^-_{\mu\nu} \partial_\nu W^+_{\mu\nu}) - A_\mu (W^+_{\mu\nu} \partial_\nu W^-_{\mu\nu} - W^-_{\mu\nu} \partial_\nu W^+_{\mu\nu}) - A_\mu (W^+_{\mu\nu} \partial_\nu W^-_{\mu\nu} - W^-_{\mu\nu} \partial_\nu W^+_{\mu\nu}) - \frac{1}{2} g^2 W^+_{\mu\nu} W^-_{\mu\nu} + \frac{1}{2} g^2 W^+_{\mu\nu} W^-_{\mu\nu} + g^2 c_w^2 (Z^0_{\mu\nu} Z^0_{\mu\nu} - Z^0_{\mu\nu} Z^0_{\mu\nu}) - g^2 c_w^2 A_\mu Z^0_{\mu\nu} (W^+_{\mu\nu} W^-_{\mu\nu} - W^+_{\mu\nu} W^-_{\mu\nu}) - 2 A_\mu Z^0_{\mu\nu} W^+_{\mu\nu} W^-_{\mu\nu} - g_\alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_\phi (H^4 + (\phi^0)^4 + 4 (\phi^+ \phi^-)^2 + 4 (\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2 (\phi^0)^2 H^2) - g M W^+_{\mu\nu} W^-_{\mu\nu} - \frac{1}{2} g^M c_\phi^2 Z^0_{\mu\nu} Z^0_{\mu\nu} - \frac{1}{2} i g [W^+_{\mu\nu} (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_{\mu\nu} (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_{\mu\nu} (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_{\mu\nu} (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g c_w (Z^0_{\mu\nu} (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g c_w M Z^0_{\mu\nu} (W^+_{\mu\nu} \phi^- - W^-_{\mu\nu} \phi^+)) + \frac{1}{2} g c_w \phi^0 \partial_\mu \phi^0 + \frac{1}{2} g c_w \phi^+ \partial_\mu \phi^+ + \frac{1}{2} g c_w \phi^- \partial_\mu \phi^- + \frac{1}{2} g c_w \phi^0 \partial_\mu \phi^0 + \frac{1}{2} g c_w \phi^+ \partial_\mu \phi^+ + \frac{1}{2} g c_w \phi^- \partial_\mu \phi^-]

\]
\[i g s_w M A_\mu (W_{\mu}^+ \phi^- - W_{\mu}^- \phi^+ ) - i g^{-\frac{2 g^2}{2 c_w}} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \]
\[i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{2} g^2 W_{\mu}^+ W_{\mu}^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \]
\[\frac{1}{4} g^2 c_w Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2 (2 s_w^2 - 1) \phi^+ \phi^-] - \frac{1}{2} g^2 c_w Z_\mu^0 \phi^0 (W_{\mu}^+ \phi^+ + W_{\mu}^- \phi^+) - \frac{1}{2} i g^2 c_w Z_\mu^0 H (W_{\mu}^+ \phi^- - W_{\mu}^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_{\mu}^+ \phi^- + W_{\mu}^- \phi^+) + \]
\[\frac{1}{2} i g^2 s_w A_\mu H (W_{\mu}^+ \phi^- - W_{\mu}^- \phi^+) - g^2 s_w (2 c_w - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \]
\[g_1 s_w A_\mu A_\mu \phi^+ \phi^- - \bar{\psi}^\lambda (\gamma \partial + m_e) \psi^\lambda - \bar{\psi}^\lambda \gamma \partial \nu^\lambda - \bar{\psi}^\lambda (\gamma \partial + m_e) \psi^\lambda - \]
\[\bar{d}_{\lambda}^\mu (\gamma \partial + m_d) d_{\lambda}^\mu + i g s_w A_\mu [-(\bar{\psi}^\lambda \gamma^\mu \psi^\lambda) + \frac{2}{3} (\bar{u}_{\lambda}^\gamma \gamma^\mu u_{\lambda}^\gamma) - \frac{1}{3} (\bar{d}_{\lambda}^\gamma \gamma^\mu d_{\lambda}^\gamma)] + \]
\[\frac{i q}{4 c_w} Z_\mu^0 [(\bar{d}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{\psi}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) \nu^\lambda) + (\bar{u}_{\lambda}^\gamma \gamma^\mu (4 s_w^2 - 1 - \gamma^5) \nu^\lambda)] + \]
\[\frac{i q}{2 c_w^2} W_{\mu}^+ [(\bar{d}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{\psi}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) \nu^\lambda) + (\bar{u}_{\lambda}^\gamma \gamma^\mu (4 s_w^2 - 1 - \gamma^5) \nu^\lambda)] - \]
\[\frac{i g}{2 c_w^2} M [-(\bar{d}^\lambda \gamma^\mu (1 - \gamma^5) \nu^\lambda) + \phi^+ (\bar{\psi}^\lambda (1 + \gamma^5) \nu^\lambda)] - \]
\[\frac{i g}{2 c_w^2} M [H (\bar{d}^\lambda \gamma^\mu (1 - \gamma^5) \nu^\lambda) + \phi^+ (\bar{\psi}^\lambda (1 + \gamma^5) \nu^\lambda)] - \]
\[\frac{i g}{2 c_w^2} M \phi^0 (\bar{d}^\lambda \gamma^5 d_{\lambda}^\mu) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \]
\[\frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_{\mu}^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_{\mu}^- (\partial_\mu \bar{X}^+ X^- - \)
\[\partial_\mu \bar{X}^0 Y) + i g c_w W_{\mu}^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^- X^0) + i g s_w W_{\mu}^- (\partial_\mu \bar{X}^- Y - \]
\[\partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \]
\[\partial_\mu \bar{X}^- X^+) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \]
\[\frac{1 - 2 g^2}{2 c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2 c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \]
\[i g M s_w [\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+] + \frac{1}{2} g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \]
$L = L_{\text{SM}} + \sum \frac{\phi_n}{\Lambda^n}$

- Effects of $\phi_n$, $\sim \left(\frac{E}{\Lambda}\right)^n$.
- What is $\Lambda$?
- LHC, all $\mathcal{O}_n$
- LEP & al., $\mathcal{O}_6 = (H^\dagger D_\mu H)^2, \ldots$
- flavour mixing, $\mathcal{O}_6 = (\overline{s}\gamma_\mu d)^2, \ldots$
- proton decay, $\mathcal{O}_6 = q\overline{q}q\overline{q}, u^c u^c d^c e^c, \ldots$
Probes of generic new physics:

- LHC, $\Lambda \gtrsim$ TeV
- LEP & al., $\Lambda \gtrsim 1 - 10$ TeV
- flavour mixing, $\Lambda \gtrsim 10^{3-5}$ TeV
- proton decay, $\Lambda \gtrsim 10^{13}$ TeV
∃ 1 measurement of $\Lambda$:

- $\nu$ masses, $\mathcal{O}_5 = (LH)^2$
- $\Rightarrow \Lambda \sim 10^{10} \text{ TeV}$

This is evidence for, not against, the SM!
Other ‘evidence’ for $\Lambda$:

- Dark Energy $\implies \Lambda \sim 10^{-3}$ eV!
- Dark Matter: $\frac{\Delta \Lambda}{\Lambda} \sim 10^{80}$!
- Baryogenesis $\implies \Lambda \lesssim M_P$!
So why did we build the LHC?!
We built the **LHC** to answer two qq:

- How is electroweak symmetry broken?
- Is the weak scale natural?
We built the LHC to answer two qq:

- How is electroweak symmetry broken? Via the Higgs mechanism.
- Is the weak scale natural?
Is the weak scale natural?
An answerable question.
∃ 1 troublesome operator

- $\mathcal{O}_2 = H^\dagger H$
- $\mathcal{L} \supset \Lambda^2 H^\dagger H \implies \Lambda \sim 100 \text{ GeV}$
- naturalness vs. fine-tuning/anthropics . . .
LHC, $Λ \gtrsim \text{TeV}$
LEP & al., $Λ \gtrsim 1 - 10 \text{ TeV}$
flavour mixing, $Λ \gtrsim 10^3 - 5 \text{ TeV}$
proton decay, $Λ \gtrsim 10^{13} \text{ TeV}$

LHC new physics cannot be generic.
Rules out, e.g., a theory with

- 100s of sub-TeV particles
- sizable couplings
- new flavour structures $\neq y^u, y^d, y^e$
- no accidental $B$ or $L$ symmetry

a.k.a. SUSY!
Our predicament requires baroque new physics . . .
e.g. 1/2: unnatural SUSY

Dimopoulos & Giudice
The Mona Lisa of Physics

Cúmpulsory Natural SUSY

1500 \rightarrow \tilde{g}

400 \rightarrow \tilde{t}_{L,R}, \tilde{b}_L

120 \rightarrow h

Unavoidable tunings: \( \left( \frac{400}{m_{\tilde{t}}^e} \right)^2, \left( \frac{4 m_{\tilde{t}}^e}{M_{\tilde{g}}} \right)^2 \)
Unnatural SUSY

**Figure 5:** Expected and observed exclusion limits at 95% C.L. on all limits at 95% CL.
e.g. 2/2: composite Higgs
e.g. 2/2: composite Higgs

- as plausible as SUSY
- similar resources should be devoted to it
A rhetorical question: What if $\not\exists$ Higgs?
What if $\not\exists$ Higgs?

- An ‘almost perfect’ rendition of EWSB!
- QCD has a natural scale $\sim$ GeV
- Global $\chi$SB: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- Gauge $\supset SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$
- (But $m_{W,Z} \sim$ GeV)
QCD Colour $\rightarrow$ Technicolour

- natural scale $\sim 100$ GeV
- Global $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- Gauge $\supset SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$
- A perfect, natural rendition of EWSB
- (But no Higgs, flavour, EWPT, …)
Technicolour $\rightarrow$ Composite Higgs

- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ is equivalent to $SO(4) \rightarrow SO(3)$
- Generalize to $SO(n+1) \rightarrow SO(n)$
Geography of $SO(n+1) \to SO(n)$ via proof by example.
Consider $SO(2) \rightarrow SO(1)$:

- There is 1 Goldstone boson: an angle
Consider $SO(3) \rightarrow SO(2)$:

- There are 2 Goldstone bosons: latitude and longitude.
Now gauge $SO(2) \subset SO(3)$:

- Rotations about a preferred direction, cf. Earth’s axis
- Goldstone boson $\rightarrow$ pseudo-GB
- Gets potential and coupling to gauge fields
- cf. temperature on Earth
Consider $SO(5) \rightarrow SO(4)$:

- There are 4 Goldstone bosons: angles of $S^4$
- They are a $2\frac{1}{2}$ of $SU(2) \times U(1)_Y \subset SO(4)$, viz. the Higgs field, $H$
- Gauging $SU(2) \times U(1)_Y$ plus coupling to $t$ generates $V(H)$ and $HWW, H\gamma\gamma$ etc
- a.k.a. the Minimal Composite Higgs model

Agashe, Contino, & Pomarol, 0412089
The minimal composite Higgs model

- $\Delta S \sim \theta^2 \implies 20\%$ tuning
- This is a lot better than SUSY
Phenomenology of composite Higgs models

- Natural because strongly-coupled
- We cannot compute!
- Use same tricks for QCD: symmetry, chiral Lagrangians, …
- Simplified models
Phenomenology of composite Higgs models: bad news

- Departures from SM in e.g. $H$ couplings $\propto \theta^2 \sim 20\%$
- Generic resonance masses $\sim 4\pi v/\theta \sim$ few TeV
Phenomenology of composite Higgs models: good news

- Naturalness $\Rightarrow$ light, fermionic top partner

- dof: $SO(4)/SO(5)$ reps, compositeness, mass, few couplings

- e.g. $1 = T$ or $4 = (B, T, T', X_{\frac{5}{3}})$ of $SO(4)$

Contino, da Rold & Pomarol, 0612048

De Simone et al., 1211.5663
Pair production of $X_{\frac{5}{3}}^3$

$m > 770 \text{GeV}$
Single production dominates at high mass/coupling

M4s, M15

M414, M114

Optimize 4th gen. searches for forward jets

De Simone et al., 1211.5663
- a huge amount of work to be done, by theorists and experimentalists
- we must do the best we can with LHC14
What if we come up empty-handed?
We will, nevertheless, have answered both questions.
We built the **LHC** to answer two qq:

- How is electroweak symmetry broken? Via the Higgs mechanism.
- Is the weak scale natural? No.
At least our hubris will be profound.
“So many centuries after the Creation, it is unlikely that anyone could find hitherto unknown lands of any value.” Spanish Royal Commission, 1490
“The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.... Our future discoveries must be looked for in the sixth place of decimals.” Michelson, 1894