The Practice of Naturalness:
An Historical-Philosophical Perspective

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Outline

- Naturalness: Questioning the premise
- The actual story (in our view):
  - First phase (1970s): Naturalness in theoretical practices
  - Second phase (1979-84): The rise of the naturalness problem
  - Third phase (1985-2012): From a problem to a general principle
  - Fourth phase (2012-today): A "post-naturalness era"?
- Conclusions: Practices, problems, principles
- Moral: Lessons from history

Questioning the premise

Shared premise in recent debates:

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Here: A look back, questioning the premise.

How: By looking not just at the definitions, but at the practice of naturalness

First phase: the 1970s

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- Renormalization and SSB are studied as means to "naturally" establish relationships between parameters:
  - "A natural explanation of the approximate symmetries in nature" (**Weinberg**, 1972).
  - "A natural mechanism for mass hierarchy" (**Georgi/Glashow**, 1972).
  - **Georgi/Pais**, "Calculability and naturalness in gauge theory" (1974): a "natural" relation has only finite counterterms thanks to SSB.
- The absence of fine-tuning in GUTs can be "natural", too: "a gauge hierarchy would be physically compelling only if it occurred naturally" (**Gildener**, 1976).

NB: No "aesthetic" or "philosophical" principles, *only situated plausibility assumptions*.

Wilson (1971)

Prominent example:

Kenneth Wilson, "Renormalization group and strong interaction" PRD (1971)

→ later on seen as a seminal reference for the naturalness principle.

In fact, what did Wilson say?

All generalized mass terms must break an internal symmetry. [...]

It is interesting to note that there are no weakly coupled scalar particles in nature;

scalar particles are the only kind of free particles whose mass does not break either an internal or a gauge symmetry.

→ The Higgs mass naturalness problem?

Let us take a closer look at Wilson's goals, arguments and results....

- Context: no Standard Model yet!
- Wilson's agenda:
  - Semi-quantitative study of renormalization group equation (building mainly upon **Gell-Mann&Low**).
  - In particular, obtain conditions for values of (strong) coupling constants.
- Wilson's starting point: renormalization group equation for $m = 0$ (RGE0):

$$\frac{de_\lambda^2}{d(ln\lambda^2)} = \psi(0, e_\lambda^2)$$

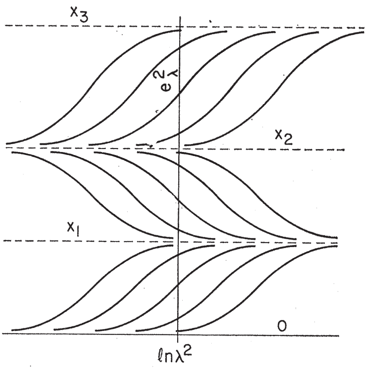
(e = coupling constant, λ = renormalization parameter)

- Wilson's reflection: General analysis $\rightarrow$ "a hopeless task", but...

. a formal analogy to nonlinear mechanics and electric circuits may provide semi-quantitative understanding.

Wilson's analogy

Three kinds of solutions for $\lambda \to \infty$: **(a)** fixed point, **(b)** limit cycle, **(c)** other (left out by Wilson as too difficult). Wilson assumes that in general **case (a)** obtains:



Question: Is this behaviour valid for all momenta?

Two physical cases

1) The model for strong interactions is valid in isolation for all momenta $\Rightarrow$ the relevant RGE is always valid.

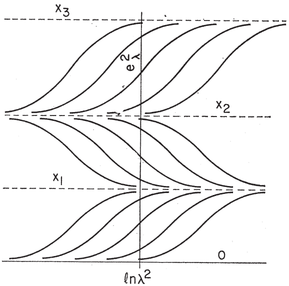
2) For a physical cutoff Λ, corrections due to weak and electromagnetic interactions become relevant $\Rightarrow$ the initial RGE is not valid for $\lambda \rightarrow \Lambda$, and so, in that limit, e_λ will not go towards the fixed point, but will be "random".

Differences to later, allegedly "Wilsonian" views:

- No unification of forces, no physical cutoff assumed - both 1) and 2) are possible!
- Near the cutoff scale, the original RGE is not valid anymore.
- IF the cutoff is there, Wilson claims that one can derive from the RGE some information on the low-energy theory...

Consequences of a physical cutoff

- IF there is a physical cutoff Λ, THEN e_Λ has a "random" value.
- IF e_Λ lies between x_1 and x_3, THEN for decreasing λ it will obey the RGE and go towards the infrared fixed-point x_2.



→ With a physical cutoff, infrared fixed points of RGE become important!

→ For $\lambda << \Lambda$, all parameters will either decrease or increase with λ.

What about mass terms?

- Generalized mass terms (i.e. $\frac{m}{\lambda}$) are large for small λ.
- They are small for $m << \lambda << \Lambda$ (scaling invariance)

$\rightarrow$ They decrease when λ increases

[Decreasing parameters] will be very small indeed when λ is of order Λ. It is hard to see how this can come about unless these couplings constants also break a symmetry [of the "cutoff" theory].

[...] In particular, all generalized mass terms must break an internal symmetry.

[...] It is interesting to note that there are no weakly coupled scalar particles in nature; scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry.

This discussion can be summarized by saying that mass terms must be "protected" from large corrections at large momenta due to various interactions.

Wilson's lesson

- Wilson was NOT imposing a condition based on some aesthetic principle, but was rather trying to interpret physically the mathematical results obtained thanks to a series of assumptions.
- He did not assume that a physical cutoff necessarily exists.
- He did not assume that at the cutoff scale the original RGE provides information on running constants.
- He regarded the absence of elementary scalars as indication that a cutoff may exist, and not the reverse!

Afterwords, however: Wilson's argument reinterpreted in terms of naturalness.

Second phase: 1979-84

- Both Wilson's arguments and other ones are subsumed unter the term naturalness and repurposed to serve new goals:
  1) Show that there is a problem with the Standard Model (by now well established).
  2) Suggest that one or the other model of new physics can solve it.
- **Susskind** (1979), **'t Hooft** (1980), **Veltman** (1981) propose different, yet related reflections on "naturalness´´ building upon previous ideas.
- 1981: Naturalness and SUSY (**Veltman**; **Ellis/Gaillard/Zumino**).

Susskind/'t Hooft/Veltman

Susskind (1979):
The radiative corrections to the Higgs mass "must be adjusted to the 38th decimal place. [...] Such adjustments are unnatural and will be assumed absent in the correct theory".

$\Rightarrow$ Technicolor!

't Hooft (1980):
Naturalness as a "dogma": "at any energy scale μ, a physical parameter α_μ is allowed to be very small only if the replacement $\alpha_\mu = 0$ would increase the symmetry of the system."

$\Rightarrow$ No technicolor!

Veltman (1981):
[In perturbative expansions] "radiative corrections are supposed to be of the same order (or much smaller) than the actually observed values."

$\Rightarrow$ Supersymmetry!

Wilson vs Susskind/'t Hooft/Veltman

- Susskind/'t Hooft/Veltman: "naturalness" is considered at very high energy - Wilson considers low and middle energy behaviour.
- Susskind/Veltman: a physical cutoff exists due to unification or gravity - Wilson: at higher energies strong interactions may not anymore be dealt with in isolation.
- Susskind: corrections from the low-energy theory are considered at the cutoff - Wilson: at the cutoff the RGE of the low-energy theory is not valid anymore.
- 't Hooft: the unnaturalness of unprotected differences in magnitude as a dogma - Wilson: scalar mass terms are forbidden on the basis of the RGE.

Ellis, Gaillard & Zumino: Naturalness and SUSY

Ellis/Gaillard/Zumino (1980), “A GUT obtained from broken supergravity”.

- **Aim**: Present a SUSY-GUT with preons which solves the gauge hierarchy problem ("unnatural" fine-tuning in GUTS) and includes gravity - no SM naturalness problem!

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Ellis/Gaillard/Zumino (1981), "Superunification".

- **Aim**: Present (again) a SUSY-GUT with preons, noting how it solves various naturalness problem(s).
- Various arguments (Susskind (1979), GUT-fine tuning, cosmology...) now subsumed under the term "naturalness".

  $\rightarrow$ SUSY can solve the problem!

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- Definition of a “N-problem”: “We have a strong N-problem whenever the set of theories which even remotely resemble our world is a tiny subset of all the acceptable theories”.
- Cure: “We must cure the problem by slicing the latter class down to size.. by finding new principles which render most of its members unacceptable" (ex: symmetry principles)

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- Cure: “We must cure the problem by slicing the latter class down to size.. by finding new principles which render most of its members unacceptable" (ex: symmetry principles)
- Use of N-arguments: “Today arguments of N occupy an important place in theoretical physics, helping us distinguish good theories from bad ones.”

  “And yet N seems to be one of the best kept secret of physicists from the public, a secret weapon for evaluating and motivating theories of the world on its deepest levels.”

- Nelson’s standpoint:: “N sometimes gives poor counsel.”

Third phase: 1985-2012

- General consensus: SM has a naturalness problem.
- Many *different definitions* of naturalness coexist.
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→ For example:

- Naturalness and SUSY, pre-LEP 1 → Barbieri/Giudice (1988) (on “Upper bounds on supersymmetric particle masses”, based on the “naturalness” criterion): it would be unnatural not to find superpartners at LEP...
- Naturalness and SUSY, post-LEP 1 → Anderson/Castaño (1995): ... but “new measures of fine-tuning” for “natural” supersymmetric model-building can be defined after no superpartners are found (shortcomings of Barbieri-Giudice prescription for upper bounds on superparticle masses).
- Naturalness, afterwards:
  - Extra-dimensional models, too, can solve a hierarchy/naturalness problem (Randall/Sundrum (1999); Arkani-Hamed/Dimopoulos/Russell (2001); ....)
  - ...

Fourth phase: 2012–

- LHC results throw doubts on the existence of a naturalness problem (however defined).

  $\rightarrow$ Ex: "Naturalness under stress" (M. Dine, 2015); "The Dawn of the Post-Naturalness Era" (G.F. Giudice, 2017); ..

- Apparently as a reaction, interest grows in discussing a naturalness principle allegedly guiding research in the last decades.

- Yet (as seen): until recently, naturalness was not in fact a *general principle*, but rather a flexible conceptual tool constructed and optimized for pursuing specific goals in BSM-model-building.

Conclusion: Practices, problems, principles

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  a) Arguments that the Standard Model has a naturalness problem.
  b) Show that some specific model can solve it.

  → The goals shaped the concept(s), and not the reverse - the vagueness of naturaless was an asset!

  → Empirical tests expected rather in the far future.

  → Guiding/heuristic role: not of a principle, rather of a problem.

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THANK YOU!