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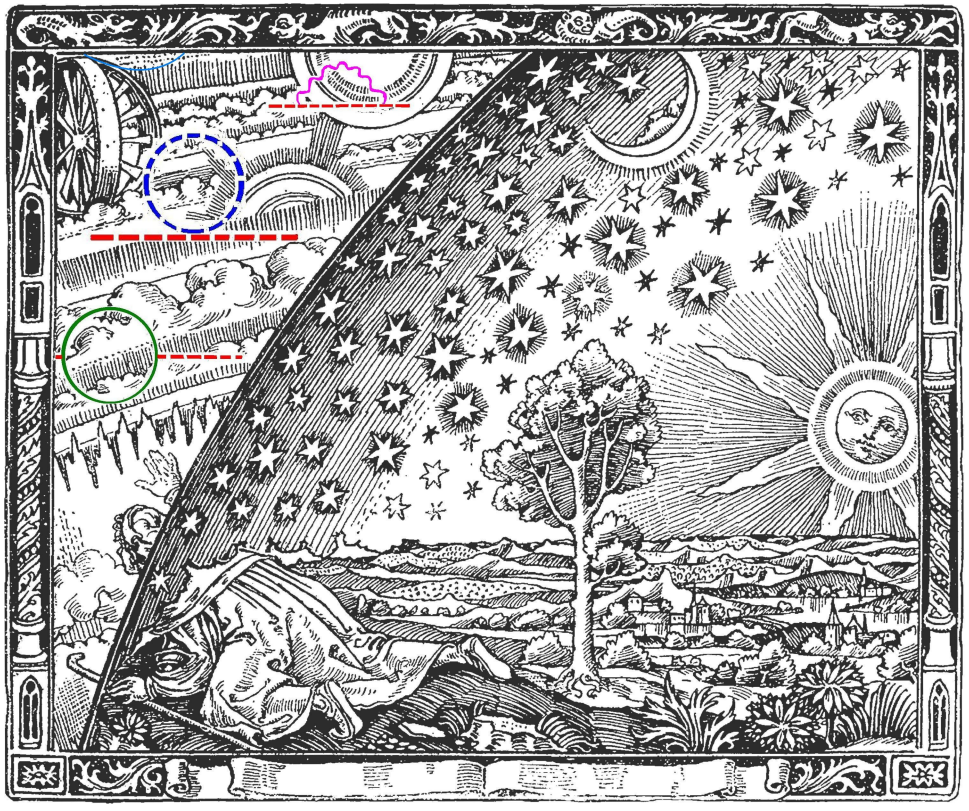
Naturalness and the hierarchy problem in historical-philosophical perspective

Aims of my talk:

- present some historical-philosophical reflections on naturalness and the hierarchy problem
- offer an idea of how research in the humanities approaches HEP

WARNING: "my" approach is integrated history and philosophy of science (&HPS)



"Naturalness" and "hierarchy problem(s)" (N/HP) today:

- noncompelling character ("aesthetic", "philosophical")
- interconnected in various formulations, e.g.:
  (a) $M_{EW} << M_{Planck}$ ----> unnatural! (alt. e.g. $m_{u,d} << m_{top}$)
  (b) real cutoff scale ~ M_{Planck} ---> unnatural fine-tuning of M_{Higgs}
  (c) "small" ratios are natural only if "protected" by symmetry

Physicists' standpoint: different formulations of problematic aspects of the Standard Model ---> search for physics beyond it!

Philosophers's questions (a choice): is it one problem or more?

- are these only "aesthetical" issues, or physical ones?
- *how come* there are multiple formulations?
- does this "multiformity"/"vagueness" contribute to the production of scientific knowledge? (Historical examples (energy, relativity) suggest that it might...)

The &HPS approach: look back in time.....

1972-1978 - early phase: two distinct threads

(1) "naturalness": spontaneous symmetry breaking is "natural"

Georgi and Pais (1974): *"Calculability and naturalness in gauge theories": "In a theory with spontaneously broken symmetry (...) the masses and coupling constants appearing in the Lagrangian will not be independent phenomenological parameters. Rather there will be zeroth-order relations between these quantities, the corrections to which are finite. We will call such relations "natural"."*

(2) "(gauge) hierarchy problem" - problem of fine-tuning in GUT's

Gildener (1976): "Gauge-symmetry hierarchies": "A gauge-symmetry hierarchy is said to occur if some of the gauge symmetries of a theory are much more strongly broken than others [e.g. GUT's. He tries to "naturally" break GUTs with SSB, but...] ...unfortunately, the hope of radiatively inducing a natural gauge hierarchy has been frustrated by our attempts."

Summary - early phase (1971-1978):

- spontaneous symmetry breaking (and more in general "symmetry breaking") as a tool to introduce "natural" parameters, ratios (i.e. not put in by hand)
- no connection between naturalness and (absence of) fine-tuning
- "gauge hierarchy problem" specific to GUTs

Turning point: 1979-81 - Three papers: Susskind, 't Hooft, Veltmann

- different, yet related reflections building upon previous ideas
- each author has his agenda, his interests, his methods

it is worth reconstructing the "finer differences", as they constitute the material from which all later formulations of nte naturalness/hierarchy problem will emerge

Leonard Susskind, Phys. Rev. D20 (1979) 2619

aim of the paper: introducing "heavy-color" (later: "technicolor")

> ***"(the) concept of naturalness requires the observable properties of a theory to be stable against minute variations of the fundamental parameters. The basic underlying framework of discussion of naturalness assumes the existence of a fundamental lenght scale k^{-1} (~ M_{Planck}) which serves as a real cutoff. [ref. to K. Wilson] The principle of naturalness requires the physical properties of the output at low energy to be stable against small variations of m_0, g_0 (...) To illustrate a case of unnatural adjustment consider a particle which receives a self-energy which is quadratic in k*** **[here usual discussion of Higgs quadratic divergences follows]".**

- **a real cutoff exists, divergences have physical significance**
- **unnaturalness of elementary Higgs due to fine-tuning**
- **symmetries play no role**

conclusion: composite Higgs ("heavy color") instead of SM Higgs

Gerhard 't Hofft, Proceedings NATO adv. study institute (1980)
aim: development of heuristic notion of "naturalness" and its use to criticise composite Higgs theories (Dimopoulos and Susskind, 1979)

> *"effective interactions at a low energy scale μ_1 should follow from the properties at a higher energy scale μ_2 without the requirement that various different parameters at the energy scale μ_2 match with an accuracy of the order μ_1/μ_2. That would be unnatural. (...) We now conjecture that the following dogma should be followed:*
> *- at any energy scale μ, a physical parameter $a(\mu)$ is allowed to be very small only if the replacement $a(\mu) = 0$ would increase the symmetry of the system."*

- no assumption of the existence of a real cutoff
- a clear-cut, universal definition of naturalness is given
- the definition is a "dogma"
- (broken) symmetries central - no quadratic divergences

conclusion: composite Higgs theories are not natural

Martin Veltman, Act. Phys. Pol. B12 (1981) 437

aim: formally analyzing the relationship between "infrared" (~ 300 GeV) and ultraviolet (~ 1 TeV) behaviour of particle theory

> ***"In renormalizable theories the cutoff scale is not observable (...) Nonetheless it is possible to say something by introducing the criterium of naturalness: (...) radiative corrections are supposed to be of the same order (or much smaller) than the actually observed values. (...) Symmetries may be important here, too; radiative corrections may be made small if there is a symmetry guaranteeing this smallness(ref. to 't Hooft) one of the most interesting applications concerns the Higgs mass in the standard model (ref. to Susskind)." Two "gaps" in Susskind: (1) " cut-off dependence requires a specification of the cut-off mechanism" (2) "there may be an underlying supersymmetry that leads to cancellations of the quadratic divergencies"***

- naturalness linked to radiative correction and thus to symmetries

- less general than 't Hofft

- premise of real cutoff accepted, attempts at refining it [not final]

conclusion: SUSY may solve "this" naturalness problem!

The roots of the multiformity of naturalness/hierarchy problems:

- all three authors connect "naturalness" with a problem of matching two very different energy scales
- Susskind, Veltman need to assume a cutoff to define naturalness
- for 't Hooft differences in magnitude are in themselves unnatural (unless "protected" by (broken) symmetry)
- with 't Hooft's definition one can argue for new physics at energies where the Standard Model become unnatural
- Susskind interprets physically the divergences in cutoff regularization and so argues for the unnaturalness of the Higgs
- Veltmann attempts to refine Susskind's approach and notes that the "naturalness problem" can be solved by supersymmetry
- 't Hofft's naturalness notion may serve as very broad heuristic guideline in model-building with (broken) symmetries

Epilogue: naturalness/hierarchy problem as a flexible heuristics

1981-1984: many authors note how supersymmetry ensures the absence of the quadratic divergences in the Higgs mass

some authors also notice how supersymmetry, thanks to the same mechanism, also helps solve the "gauge hierarchy problem" of GUTs (the "little hierarchy problem")

mutual feedback of supersymmetry, naturalness, hierarchy (the solutions helps frame the problem - well-known in history!)

1984: "first string revolution": strings as a "natural" theory!

1985-...: naturalness and hierarchy problem ($M_{EW} << M_{Planck}$) as reasons to search for new physics at the TeV-scale (LEP, LHC)

1995-...: small, nonzero neutrino masses, high top-quark mass

-----> *new hierarchy problems to be solved!*

- "measures of fine-tuning" as heuristics in SUSY model-building
- extra-dim. models as solutions to the "big" hierarchy problem