A Philosophical Perspective on Problems in Physics

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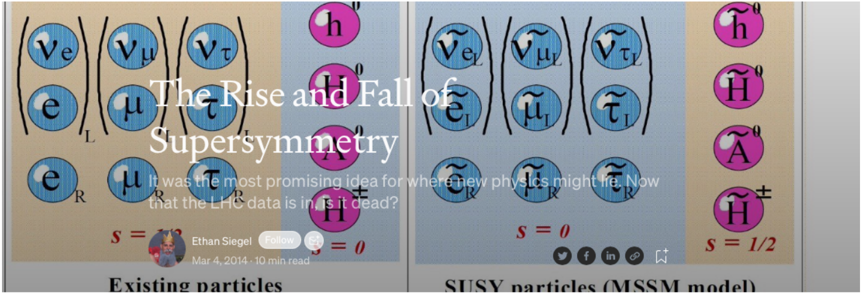
Theory Development and Assessment: Supersymmetry



Source:https://medium.com/starts-with-a-bang/the-rise-and-fall-of-supersymmetry-c6ef51bea56b

Theory Development and Assessment: Supersymmetry

"It is not an exaggeration to say that most of the world's particle physicists believe that supersymmetry must be true."

(J. Lykken & M. Spiropulu in Scientific American May 2014; my emphasis)

Theory Development and Assessment: Supersymmetry

Arguments for supersymmetry:

- can solve the naturalness problem of the Higgs mass
- can solve the dark matter problem
- can solve the baryon asymmetry problem
- can solve the problem of gauge coupling unification
- ...

Theory Development and Assessment

Theory development and assessment depend on the

- empirical assessment of scientific theories
- problem-centric solution space assessment
- ...

Outline

1. What is a Scientific Problem?
2. How Do Problems Relate to Their Solutions?
3. How Problems Shape Theory Development?
4. Which Problems Are Worthy of Pursuit?

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What Is a Scientific Problem?

- Positivist model of problems: empirical fact in search of an explanation or prediction
- K. Popper (1972): problem situations = (Problem, Framework, Theoretical Background)
  - Example: (tides, circular inertia, copernican viewpoint)
- J. Agassi (1964): the importance of metaphysics in defining problems
- L. Laudan (1977): empirical and conceptual problems
- J. N. Hattiangadi (1978): problems have the logical structure of inconsistencies
- T. Nickles (1981): Constraint-Inclusion Model
- G. P. Agre (1982): considers the relation between problems and the agents' attitudes towards them
- Elliott (2019): extends Nickles account within a broader more general framework of research problems

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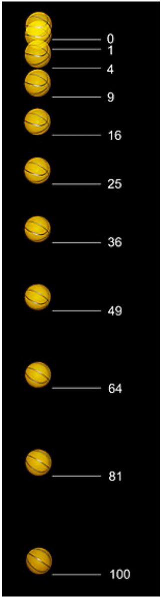
Which Empirical Fact?

- Consider a falling object
- What kind of data to collect?
  - mass
  - composition
  - size
  - colour
  - position
  - ...



Source of picture: Wikipedia

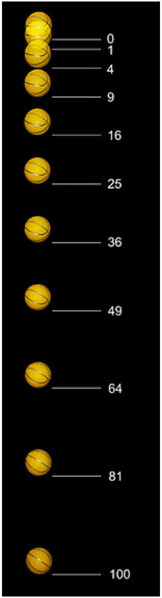
Which Empirical Fact?

But though this sort of fact-collecting has been essential to the origin of many significant sciences, anyone who examines, for example, Pliny's encyclopedic writings or the Baconian natural histories of the seventeenth century will discover that it produces a morass. One somehow hesitates to call the literature that results scientific. The Baconian "histories" of heat, color, wind, mining, and so on, are filled with information, some of it recondite. But they juxtapose facts that will later prove revealing (e.g., heating by mixture) with others (e.g., the warmth of dung heaps) that will for some time remain too complex to be integrated with theory at all.

T. S. Kuhn (1970). The structure of scientific revolutions. University of Chicago press, p. 16.
Source of picture: Wikipedia

What do we want to explain/predict?

- Why it falls?
- What makes it fall?
- How fast it falls? ...



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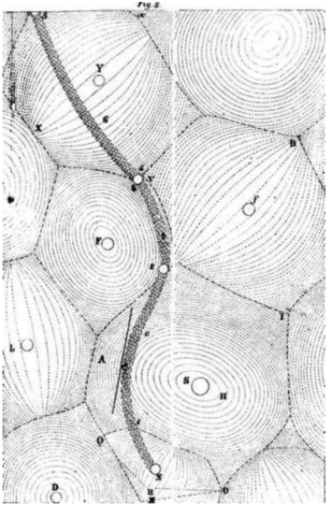
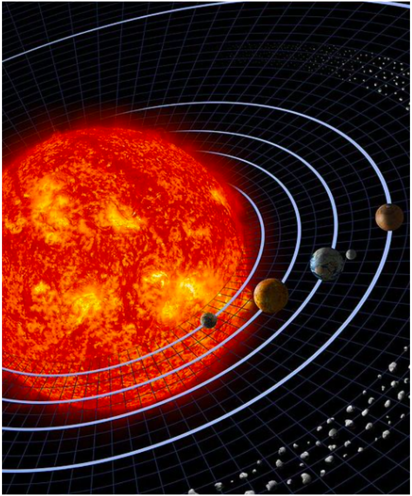
Example of Kuhn-Loss: Direction of Orbits and Descartes' Vortex Theory





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List of Unsolved Problems

- What is Dark Matter
- What is Dark Energy
- Baryon Asymmetry Problem
- Hierarchy Problem
- Small Neutrino Mass Problem
- Small Higgs Mass Problem
- Strong CP Problem
- Gauge Coupling Unification
- Finding a consistent theory of Quantum Gravity
- ...

List of Unsolved Problems

Empirical Problems

- What is Dark Matter
- What is Dark Energy
- Baryon Asymmetry Problem
- Small Neutrino Mass Problem
- Small Higgs Mass Problem

Conceptual Problems

- Hierarchy Problem
- Strong CP Problem
- Gauge Coupling Unification
- Finding a consistent theory of Quantum Gravity

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What Is a Scientific Problem?

Nickles' Account of Scientific Problems (1981)

- A Scientific Problem *is* the demand that a certain goal be achieved plus a set of constraints. Let's say $< G, \mathcal{C} >$.
- There is no clear distinction between empirical and conceptual problems.
- Two scientists may disagree on the set of constraints, although sharing the same goal.
- "Problems can be reformulated in significantly (conceptually) different ways, formulated more or less completely, transformed and reduced to other problems – all without essential change in the presentation of the empirical data to be explained."
- "Formulating a good problem can be an important theoretical scientific achievement ..."

What Is a Scientific Problem?

What are the Elements of a Problem?

- empirical data
- physical assumptions
- metaphysical assumptions
- theoretical framework
- mathematical methods
- mathematical structures
- ...

The Higgs-Naturalness Problem

"Standard" formulation

- The Higgs naturalness problem arises due to huge quantum corrections to the Higgs mass.

$$
\begin{aligned}
m_{phys}^2 &= m_{bare}^2 + \delta m^2 \\
&= m_{bare}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \dots
\end{aligned}
$$

- One may take $\Lambda = M_{Pl} \approx 10^{18} GeV$.
- Observed Higgs mass is roughly $m_{phys} = 125 GeV$
- With $\Lambda \approx 10^{18} GeV$ you need some extreme fine-tuning between m_{bare} and Λ in order to get the observed Higgs mass.
- This cancellation/fine-tuning requires a very "unlikely conspiracy" between the terms.
- ... and that is a problem!

What is the Higgs Naturalness Problem

Higgs Naturalness Problem: $< G, \mathcal{C} >$ with $\mathcal{C} = \{A, B, C, D, E, ...\}$

- G: Explain the Higgs mass!
- A: $m_{phys} = 125 GeV$.
- B: There is a huge gap between M_{Pl} and M_{EW}.
- C: There is nothing 'in between' M_{Pl} and M_{EW} to affect the calculation.
- D: The QFT formalism equipped with a 'standard' interpretation.
- E: There should be no "unlikely conspiracy"
- ...

Outline

Problems and Their Solutions (Nickles, 1981)

- "Stating the Problem is half the solution!"
- Each problem constraint is a constraint on solution space.
- Solution space given by the denial of (individual) constraints.
- Each denial corresponds to a different strategy in resolving the existing tension.

What is the Higgs Naturalness Problem

Higgs Naturalness Problem: $< G, \mathcal{C} >$ with $\mathcal{C} = \{A, B, C, D, E, ...\}$:

- G: Explain the smallness of the Higgs mass.
- A: $m_{phys} = 125 GeV$.
- B: There is a huge gap between M_{Pl} and M_{EW}.
- C: There is nothing 'in between' M_{Pl} and M_{EW} to affect the calculation.
- D: The QFT formalism equipped with a standard interpretation.
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- ...

Solving the Higgs Naturalness Problem

Solutions:

- $\neg B$: Hierarchy Problem
  - Bring M_{Pl} closer to M_{EW} $\rightarrow$ extra-dimensional theories [Arkani-Hamed, Dvali & Dimopoulos (1998), Randall & Sundrum (1998)]
- $\neg C$: TeV scale physics:
  - Supersymmetric models/Little Higgs/Technicolor
- $\neg D$: Changing the standard interpretation
  - Give up on fundamental interpretations of the bare parameters [Wetterich (1984), Rosaler & Harlander (2018)]
- $\neg E$: Address the measure problem
  - Hossenfelder (2018)
  - Wells (2018)
  - Top-Down Approaches: Shaposhnikov/Wetterich (2010), String Theory

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How Problems Change?

- Scientific problems can be radically transformed.
- Any change in the constraints amounts to (strictly speaking) a change in the problem.
- Any change in the constraints can directly impact the set of possible solutions (denoted by T).

Extending $\mathcal{C}$

$$< G, \mathcal{C} > \quad \Rightarrow \quad < G, \mathcal{C}' > \quad \text{with} \quad \mathcal{C} \subset \mathcal{C}'$$

- There are two such cases:
  1. The extension is due to the explicit incorporation of tacit assumptions
     - Impact on T largely negligible, i.e. roughly $T = T'$
     - Examples: Constraint D above; symmetries represented by Lie algebras, ...
  2. The extension is due to a novel constraint not recognized before
     - Impact on T, i.e. $T' \subset T$
     - Example: new empirical data (discovery of Higgs) or implications of Bell inequalities on future completions of QM

Problem Reduction I

$< G, \mathcal{C} > \quad \Rightarrow \quad < G', \mathcal{C}' > \quad$ with $\quad G' = \neg a \quad , a \in \mathcal{C}$ and $(\mathcal{C} \setminus a) \subseteq \mathcal{C}'$

- Focus on a subproblem
- Example: $G' = \neg B$, i.e. solving the hierarchy problem.
- Example: $G' = \neg C$, i.e. finding new TeV scale physics.

Problem Reduction II

$< G, \mathcal{C} > \quad \Rightarrow \quad < G, \mathcal{C}' >$ with a less pressing $a' \in \mathcal{C}'$ replacing an $a \in \mathcal{C}$

- Find a solution such that the incompatibility decreases (Newell & Simon, 1972)
- Example: depending on the number of extra dimensions and their radii the hierarchy decreases more and more.
- Example: Finding new physics at e.g. $\mathcal{O}(10\ \text{TeV})$

Problem Reformulation

$< G, \mathcal{C} > \quad \Rightarrow \quad < G', \mathcal{C}' >$ with the solutions of $< G', \mathcal{C}' >$ of relevance for $< G, \mathcal{C} >$.

- Reformulate to a more tractable problem.
- Equivalent just in case solution space identical.
- logical equivalence does not entail cognitive equivalence (Nickles, 2005).
- Example: Go to the conformal field theory side to solve AdS problem (AdS/CFT Duality).
- Example: Solving something in 4d-Euclidean space before going back to Minkowski space.

Problem Precisification

$$< G, \mathcal{C} > \Rightarrow < G, \mathcal{C}' >, \quad \exists\ a \in \mathcal{C} \text{ and an } a' \in \mathcal{C}' \text{ s.t. } a \subseteq a'$$

- Find a more precise formulation.
- Example:
  - Replace E: There should be no "unlikely conspiracy"
  - With E': A measure of fine-tuning, which makes the cancellation "unlikely" (Barbieri and Giudice, 1988)
- More concrete program: what gave rise to that specific measure?

Problem Relaxation

$< G, \mathcal{C} > \Rightarrow < G, \mathcal{C}' > \quad \exists\ a \in \mathcal{C}$ and an $a' \in \mathcal{C}'$ s.t. $a' \subset a$

- Relaxing one of the constraints to extend solution space.
- Consider relaxing one of the axioms that determines the mathematical structure used to represent the relevant physics.
- Example: tacit constraint in representing continuous symmetries via Lie algebras.
  - Relax that constraint to graded Lie algebras (note: all Lie algebras satisfy the axioms of graded Lie algebras but not all graded Lie algebras those of Lie algebras).
  - Allowed circumventing the Coleman and Mandula no-go theorem to non-trivially combine internal and external symmetries.

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Problem Change and Historical Development

- "Cashing out" what constitutes the scientific problems of a field provides a more fine-grained analysis of the field.
  - Theory perspective ("The rise and fall of BSM physics")
  - Problem perspective ("The rise and fall of the naturalness problem")

Outline

Justification of Problems

"Justifying" a problem amounts to justifying the constraints which give rise to it.

- empirical data
- theoretical framework
- physical assumptions
- metaphysical assumptions
- mathematical methods
- mathematical structures
- ...

Justification of Problems

- Possible justifications:
  1. Empirical justification (measured Higgs mass, non-observation of anything else)
  2. Metaphysical justification (what parts of the formalism should be interpreted physically)
  3. Meta-inductive justification (no fine-tuning)
  4. Pragmatic justification
- The strength of the justifications one can give for various constraints varies significantly (from strong empirical evidence to a simple stipulation of preference).

Pursuit Worthiness of a Problem

- Determined by many additional factors, e.g.
  - fruitfulness
  - cultural/social
  - abilities/tools
  - experimental resources vs. no experimental resources

Thanks!