Theory construction by framework generalization

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Outline

1. Theory construction with sparse evidence
2. Generalized frameworks in frontier physics
3. The method of framework generalization
4. Exploratory experimentation with generalized frameworks

1. Theory construction with sparse evidence

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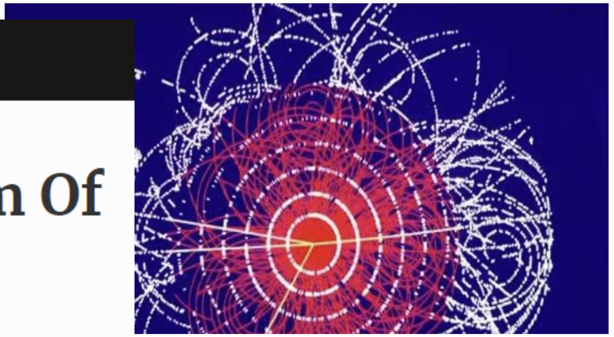
By Livescience.com published November 16, 2012



1. Theory construction with sparse evidence

- By mid-1970s, success of model-building strategies led to GUTs, (later) SUSY, string theory, and inflation as new models relevant for frontier physics.
- All make specific, concrete predictions for new empirical phenomena
  - Inflation is potentially an exception
- All tested specific, concrete predictions have failed!
- Even worse, in many cases since the 1980s we have not found anything unexpected by current theory!

1. Theory construction with sparse evidence

Model construction in frontier physics has failed to provide new, confirmed models going beyond the standard model or GR. The most obvious candidates for new models (based on methodological continuity/conservative extension) have been ruled out or disfavoured.

Despite theoretical expectations that there must be something beyond QFT and GR, we have yet to find decisive points at which either framework fails.

Model building is both very difficult and too easy without input of new, unexpected evidence.

1. Theory construction with sparse evidence

Challenges of model building:

- Too hard: Where to focus attention? What new effects should we expect from a new model?

- Too easy: Far too unconstrained; leads to a proliferation of toy models with no way to thin the herd.

1. Theory construction with sparse evidence

Lack of evidence leads to disappointment in communities, with expectations for model construction low.

E.g., “Higgs boson blues”

(Not the Nick Cave song!)

1. Theory construction with sparse evidence

When anomalous empirical evidence arises, model construction proliferates, (e.g., FTL neutrinos)

BUT, need a steady input of new evidence to weed out the inadequate models. Without new evidence, theory construction by model building will flounder.

1. Theory construction with sparse evidence

Luckily, there are other methods for theory construction! Theory construction by the method of framework generalization is very common in frontier physics today.

What is framework generalization? Start with some examples, then a more general characterization of the method.

Start with a known theoretical framework for some domain, and generalize by relaxing some subset of its core assumptions.

2. Generalized frameworks in frontier physics

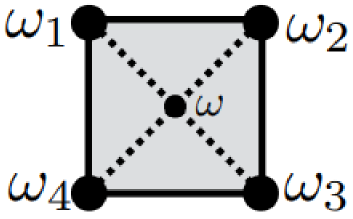
1. Quantum foundations
   - Generalized probabilistic theory space, operational reconstructions of QT
2. Gravity
   - PPN, PPF, PPE
   - Parameterized dark matter
3. Particle physics
   - Effective field theory
   - Inflation

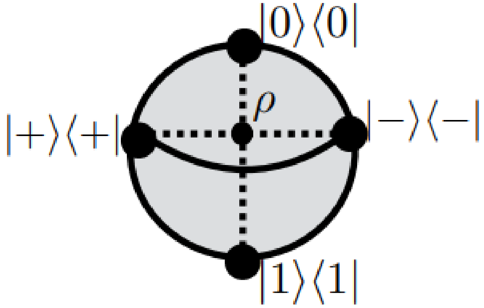
2.1 Generalized frameworks: quantum foundations

Generalized probabilistic theory framework

- Operational framework that generalizes well beyond the kinematics and dynamics of quantum theory
- Principles include: **states** encoding the probabilities of outcomes of **measurements**, and **transformations** between states
- Goal is to reconstruct quantum theory by using (physical & information-theoretic) principles to restrict the space of possible theories.

(cf. K&Müller2018, Masanes & Müller 2011)





2.2 Generalized frameworks: parameterized post-Friedmann

- Parameterized formalism to compare theories that modify GR on cosmic scales
- Relationships between scalar spacetime perturbations on cosmic scales Ψ, gravitational potential Φ, and matter overdensity δ (Hu and Sawicki 2007)

$$-k^2\Psi(\boldsymbol{k},t) = \frac{3}{2}\Omega_m(a)(aH)^2\,\mu(k,t)\delta$$

$$\frac{\Phi(\boldsymbol{k},t)}{\Psi(\boldsymbol{k},t)} = \gamma(k,t)\,.$$

- For GR, $\mu = \gamma = 1$
- Many other parameterized frameworks in gravity (PPE, PPN, dark matter, inflation)

2.3 Generalized frameworks: effective field theory

- Start from framework of (renormalizable) quantum field theory, drop requirement of renormalizability
- Justified by renormalization group analysis: non-renormalizable terms are irrelevant at energies far below the scale at which new (unknown) physics comes in
- Greatly expands the space of possible Lagrangians

(Weinberg 1979, K & Fraser 2022)

2.3 Constructing EFTs in particle physics

Concrete top-down construction

- Start with a high-energy theory with high-mass particles M
- Set $\Lambda < M$, define EFT as general Lagrangian containing interactions of all fields with $m < \Lambda$
- Use matching conditions to (perturbatively) set values for EFT couplings
- E.g., Fermi theory as EFT to electroweak theory

$$\mathcal{A} = \left(\frac{-ig}{\sqrt{2}}\right)^2 (\bar{\nu}_\mu \gamma^\alpha P_L \mu)(\bar{e}\gamma^\beta P_L \nu_e)\left(\frac{-i\eta_{\alpha\beta}}{p^2 - M_W^2}\right) \longrightarrow \mathcal{A} = -\frac{i\eta_{\alpha\beta}}{2\sqrt{2}} G_F (\bar{\nu}_\mu \gamma^\alpha P_L \mu)(\bar{e}\gamma^\beta P_L \nu_e)$$

2.3 Constructing EFTs in particle physics

Bottom-up perspective

- Treat EFTs as independent theories; consider the relevant dofs for domain of interest E << Λ
- Write down the most general Lagrangian consistent with chosen fields and their symmetries

$$\mathcal{L}_{\mathrm{EFT}} = \sum_{D \geq 0} \frac{\mathcal{L}_D}{\Lambda^{D-4}} = \sum_{D \geq 0} \sum_i \frac{\alpha_i O_i^{([D])}}{\Lambda^{D-4}}$$

- Group operators in terms of mass dimension: dimensionless constants

$$g_i = \frac{\alpha_i}{\Lambda^{D-4}}$$

2.3 Constructing EFTs in particle physics

Bottom-up perspective

- At energies E << Λ, most terms of mass dimension D > 4 will be suppressed. Couplings g(E) are fixed by measurement (no matching conditions needed)
- Including higher-order terms -> more precision; but must fix more couplings empirically!
- No coarse-graining -> no semi-RG
- Scaling properties of a given EFT using full-RG beta-functions (empirically confirmed use of RG)

2.3 Constructing EFTs in particle physics

In the context of the SM, can use the EFT theory space to conceptualize and organize deviations from (renormalizable) SM predictions

In principle, deviations from SM predictions provide evidence for which new (nonrenormalizable) terms are needed in the SMEFT, and bounds on their magnitude

3. The method of framework generalization

What methodology do all these examples (and more) share? How does this differ from more familiar model building?

Framework generalization: start from a well-confirmed, established theoretical framework. Elucidate the core principles and/or parameters for some domain of the framework; then generalize the framework by relaxing/removing some core principles or by parameterizing constants. Result is an enlarged, modal theory space.

3. The method of framework generalization

Framework generalization: start from a well-confirmed, established theoretical framework. Elucidate the core principles and/or parameters for some domain of the framework; then generalize the framework by relaxing/removing some core principles or by parameterizing constants. Result is an enlarged, modal theory space.

Framework generalization provides a structured means of discovery, by conservatively extending the principles/quantities of known frameworks in a principled way.

3. The method of framework generalization

Framework generalization - examples:

GPTs: relax all dynamical assumptions of quantum theory, retain textbook relationship between states encoding probabilities of outcomes, and discrete numbers of possibilities

Gravity: many examples of relaxing assumptions by *parameterization*. Take some phenomenological domain of GR, allow relationships between quantities to vary by functions of other quantities:

$$A(x,y) = \mu B(x,y) \rightarrow A(x,y) = \mu(x,y,z)\gamma(a,b)B(x,y)$$

3. The method of framework generalization

Framework generalization - examples:

EFTs: relax the requirements of (perturbative) renormalizability, retain local Lagrangian framework for describing quantum fields.

Greatly expands the space of possible Lagrangian field theories, but this class is itself restrictive (cf. Ruetsche 2018, K& Smeenk 2022)

3. The method of framework generalization

Similarity to the principle/constructive theory distinction

“There are several kinds of theory in physics. Most of them are constructive. These attempt to build a picture of complex phenomena out of some relatively simple proposition. The kinetic theory of gases, for instance, attempts to refer to molecular movement the mechanical, thermal, and diffusional properties of gases. When we say that we understand a group of natural phenomena, we mean that we have found a constructive theory which embraces them.

But in addition to this most weighty group of theories, there is another group consisting of what I call theories of principle. These employ the analytic, not the synthetic method. Their starting point and foundation are not hypothetical constituents, but empirically observed general properties of phenomena, principles from which mathematical formula are deduced of such a kind that they apply to every case which presents itself.”

Einstein (1919)

3. The method of framework generalization

Similarity to the principle/constructive theory distinction

Principle/constructive contrast is a contrast between <u>theories</u>

Model building/framework generalization is a contrast between <u>methodologies</u> for theory construction

Nevertheless, there are still interesting parallels between the two

3. The method of framework generalization

Principle theories

- Start from well-established empirical principles, construct mathematical system based on these as core axioms
- Determine constraints on what the world must be like for these principles to hold

Constructive theories

- Start from a bottom-level set of building blocks -> clear foundational ontology
- Derive measured empirical phenomena from dynamics of the entities of the theory

3. The method of framework generalization

Framework generalization

- Start from well-established theoretical framework, construct mathematical system based on generalizing some core principles
- Use experiments to constrain theory space based on these principles

Model building

- Start from a concrete model -> clear concrete dynamics and ontology
- Derive measured empirical phenomena from dynamics of the entities of the theory

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4. Exploratory experiments with generalized frameworks

In absence of predictions from concrete models, and without otherwise anomalous evidence, the process of theory construction is relatively unconstrained.

Generalized frameworks can provide structure to experimental searches, by delimiting a space of possible alternatives to current theory.

In particular, a generalized framework can turn *precision tests* of current theory into *exploratory tests* of generalized theory space.

4. Exploratory experiments with generalized frameworks

By allowing a new range of parameter values, a generalized framework expands the possibilities for phenomenological relationships.

Precision testing is one way to determine if there are small deviations from expectations of current theory; precision testing of parameters that have been generalized allows one to test the whole range of possible theories in the generalized space.

4. Exploratory experiments with generalized frameworks

Example: Precision tests of the fine-structure constant

Recent tests of the muon's anomalous magnetic moment are used to look for deviations from predictions of the (renormalized) Standard Model, which fit into the generalized framework of the SMEFT

$$a_\mu(\text{theory}) = 116\,591\,810(43) \times 10^{-11}$$ (Aoyama et al. 2020)

$$a_\mu(\text{exp}) = 116\,592\,061(41) \times 10^{-11}$$ (Albahri et al. 2021)

4.2σ tension! (cf. K&Smeenk 2020, K2021)

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4. Exploratory experiments with generalized frameworks

Precision tests repurposed to exploratory tests

- Early accounts of exploratory experiments: characterized by minimal dependence of background theory (Steinle 1997, Elliot 2007)
  - Contrasted with theory-drive experimentation
- Karaca (2017): exploratory experimentation in HEP are theory-laden
  - Characterized instead by methods that seek to expand the range of outcomes
  - Contrast with precision tests
- Precision tests in theoretical context of EFTs: exploration by elimination

4. Exploratory experiments with generalized frameworks

Generalized framework = better handling of systematic error

- Staley (2020): systematic error as a form of robustness analysis
    - Quantification of systematic error as measure of variation of a result when changes are made to a subset of modelling assumptions
- Modelling assumptions are theory-predicated
- Generalization of theory space, better understanding of possible variety of modelling assumptions = better understanding of systematic error
- General theory space = more general assumptions, not assumption-free!

4. Exploratory experiments with generalized frameworks

Drawbacks of framework generalization

- SMEFT is enormously complicated -> deviations do not tightly constrain what new terms to add to SMEFT (King et al. 2022)
- Even with known deviations, new terms do not suggest a particular underlying model
  - Feature here can become a flaw if the end goal is a concrete model
- Not assumption free! Framework still makes substantial assumptions that could be false of successor theory (Ruetsche 2018, K&Smeenk 2022)

4. Exploratory experiments with generalized frameworks

Generalized frameworks turn ordinary precision tests into exploratory experiments.

Allows for evidence to inform theory construction without specific concrete models in hand. Generalized frameworks provide a principle theory-style approach to theory construction.

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