Perturbing Realism

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Two Circumscription Problems

$T \leftarrow$ a stupendously successful physical theory

scientific realism: T is (at least approximately) true where "true" is construed non-instrumentally, non-pragmatically.

Pessimistic meta-induction: The history of science is a history of theories once celebrated and now discarded. A similar fate awaits T.

realism's divide et impera response: invoke a selection principle that identifies aspects of theories that will persist in future theories. Espouse realism about these privileged aspects.

Selection principles announced to date are suspiciously vague, unhelpfully retrospective.

empiricism. T is empirically adequate. It saves (and will continue to save) the phenomena. But it's not true.

The problem of selective skepticism: why believe T accurately describes what's not yet observed but not what's unobservable?

Effective Realism

A new development in the scientific realism debate!

Inspired by both ideologies and technologies of our best contemporary physics, the interacting quantum field theories (QFTs) making up the Standard Model of particle physics.

- ideology: the effective theory idea—successful theories aren't fundamental; they just, in their regimes of application, encapsulate the implications of underlying physics.
- technology: Renormalization Group (RG) analyses.

Effective Realism uses these to articulate a refined and resilient scientific realism.

My aim: take on Effective Realism.

My claim: A more refined and resilient empiricism will emerge. So will a common foe: fundamentalism.

(Wallace 2006); Hancox-Li 2015; J Fraser 2017, 2018; Williams 2018; Miller 2017

Rough Guide to Lagrangians, fields

A Lagrangian $\mathcal{L}$ describes a system by determining what sorts of histories are possible for it. These histories are solutions to the equations of motion determined by the Lagrangian.

One kind of system is a field $\phi(x)$, which associates a quantity with every point x of space-time.

A field-theoretic Lagrangian incorporates one or more fields $\phi(x), \psi(x)$, . . . , their spacetime derivatives ($\partial\phi(x) \ . \ . \ .$), field/particle parameters (e.g. masses m, charges), interaction "couplings" (g).

Example. Free Lagrangian for a mass m scalar field in two spacetime dimensions:

$$\mathcal{L}_0 = \partial^2\phi^2 + m^2\phi^2$$

Example. Lagrangian for such a field interacting with itself via a potential proportional to ϕ^4:

$$\mathcal{L}_{\phi^4} = \partial^2\phi^2 + m^2\phi^2 + g\phi^4$$

Free QFTs

Under good mathematical control. We can solve the equations of motion determined by a free Lagrangian $\mathcal{L}_0$, and use the solutions to build a quantum (field) theory.

Elements of the construction: states (e.g. the vacuum state $|0\rangle$) and physical magnitudes (e.g. field operators $\hat{\phi}(x)$), which cooperate to define probabilities for physical events.

$$\langle 0|\hat{\phi}(x)\hat{\phi}(y)|0\rangle := \langle \hat{\phi}(x)\hat{\phi}(y)\rangle$$

Custom: fields appearing in Lagrangians correspond to particles. The correlation function $\langle \hat{\phi}(x)\hat{\phi}(y)\rangle$ determines the probability for a complex event involving mass m scalar particles (e.g. some are created here and other annihilated over there). (Custom receives critical attention in the foundations literature.)

! Wightman reconstruction theorem (see Strocchi 2013): A theory satisfying Wightman axioms is determined by a complete set of n-point functions.

Interactions; Perturbative Approximation

Interacting QFTs. Where the action is. Not under good mathematical control. For Lagrangians like $\mathcal{L}_{\phi^4}$, we don't know how to construct exact solutions. Fallback: try to approximate solutions perturbatively.

1. Model interacting theory as slight modification of free theory:

$$\mathcal{L}(\phi, m, g) = \mathcal{L}_0 + g\mathcal{L}_I$$

   $\mathcal{L}_0 \leftarrow$ *free* Lagrangian; exact solutions $\phi_0(x)$

   $\mathcal{L}_I \leftarrow$ describes interaction. g is small! So

2. Assume solutions ϕ for full theory are well approximated by perturbative expansions around free solutions:

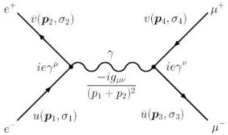
$$\phi(x) = \phi_0(x) + g\phi_1(x) + g^2\phi_2(x) + \dots$$

3. Use these approximations to calculate correlation functions, S-matrix elements, experimental cross sections — equipping the QFT with empirical content.

$$\phi(x) = \phi_0(x) + g\phi_1(x) + g^2\phi_2(x) + \dots$$

Feynman diagrams guide calculation of terms in this expansion.

Example: $e^+e^- \to \mu^+\mu^-$ in QED



But enigmatically! Individual terms in the expansion diverge. For ϕ^4 theory in d dimensions, integrals like

$$\int_0^\infty \frac{k^{d-1}}{k^2 + m^2} dk$$

(k momentum) start appearing at second order. Ultraviolet (UV) divergence. (high energy/momentum $\leftrightarrow$ short wave-length $\leftrightarrow$ UV)

Perturbative renormalization . . .

Problem: $\int_0^\infty \frac{k^{d-1}}{k^2+m^2} dk$ diverges!

Fix: "Regularization". Instead of integrating over all momentum modes, impose a UV cutoff: $\int_0^{\Lambda_{UV}} \frac{k^{d-1}}{k^2+m^2} dk$

Integral is finite. New problem: my theory is cutoff dependent!

Fix: "Renormalization." Write original Lagrangian in terms of new coefficients cleverly chosen so that as $\Lambda_{UV} \to \infty$, terms in expansion at each order converge:

$$\mathcal{L}(\phi, m, g) \underset{ization}{\overset{renormal-}{\longrightarrow}} \mathcal{L}(\phi_r, m_r, g_r, \ldots)$$

If this takes only *only a finite number* of reparameterizations, your theory is perturbatively renormalizable.

Examples: ϕ^4 theory. Quantum Electrodynamics (QED).

. . . And ambivalence

“The shell game that we play ... is technically called 'renormalization'. But no matter how clever the word, it is still what I would call a dippy process!” (Feynman 1990, 128)

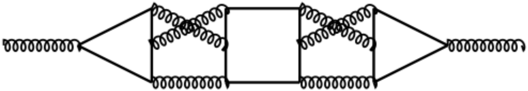


Fig. 1.2 Troublesome 14'th oder QED diagram

Typically, renormalized masses and couplings aren't supplied by calculations mediated by specific (and possibly inapt) renormalization schemes but determined experimentally.

“There exists a celebrated procedure, called renormalizaton . . . . Born as partly magic, partly suspicious manipulations on formal series with infinite coefficients, it led, when applied to QED, to finite results which were in spectacular agreement with experiment.” (Gawedzki 1986, 1279-1280)

Perturbative QFT's "Real Problem"

Perturbative renormalization doesn't *articulate a model* of physical reality. It's an *approximation technique*. Why does the technique work so well?

> *The success of the perturbative approach is mysterious, I suggest, precisely because it dodges the question of what an interacting QFT is. . . . [There is] an absence of any non-perturbative characterization of the system of interest. While I have argued that this does not render perturbative QFT incoherent it undercuts the possibility of telling a physical story which could explain its success.(J Fraser 2017, 17, 18)*

The RG: Basic Picture

Theory $\leftrightarrow \mathcal{L}$, a f'n of fields and their derivatives. Code $\mathcal{L}$ by an infinite list g_i of "coupling" coefficients for these terms.

$\mathcal{L}^\ell$: such a Lagrangian, governing phenomena at scale $\ell \leftrightarrow g_i(\ell)$

An element of a space $\mathcal{T}$=*Lagrangians* $\times$ *scales*.

Another element: $\mathcal{L}^\Lambda$, a Lagrangian describing physics at a more fundamental (higher energy/shorter length) scale Λ than "our" scale μ.

Burning question: What does $\mathcal{L}^\Lambda$ imply about physics at our scale μ? Introduce a gadget $R_{\mu\Lambda}$ tracking this:

$$\mathcal{L}^\mu = R_{\mu\Lambda}\mathcal{L}^\Lambda$$

$\mathcal{L}^\mu$ is the scale μ Lagrangian that duplicates the correlation functions at scale μ defined by $\mathcal{L}^\Lambda$.

$\mathcal{L}^\mu$ is a.k.a. the effective (at scale μ) Lagrangian induced by the underlying Lagrangian $\mathcal{L}^\Lambda$.

The family of transformations $R_{\mu\Lambda}$ acting on $\mathcal{T}$ constitutes the "renormalization group" (RG) ($\leftrightarrow \frac{dg_i(\mu)}{d\Lambda}$)

Worries; Hope

Picture: our QFTs are low-energy effective theories induced by (unknown) higher energy theories, and connected to them by an RG flow.

Worry:

- This isn't a non-perturbative characterization of anything!– We still don't know the high energy theory $\mathcal{L}^{\Lambda}$
- What stops $\mathcal{L}^{\mu}$ from being an intractable function of infinitely many fields? How is the RG flow going to rescue effective physics from ineffability?

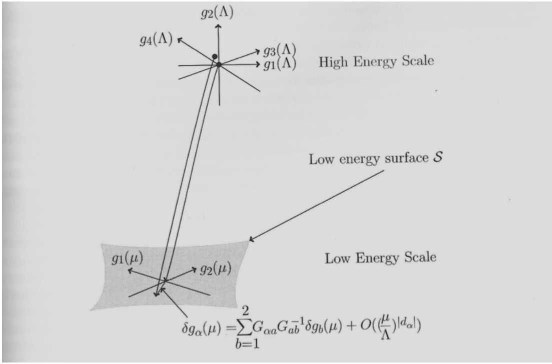
Hope: Could the RG's action on $\mathcal{T}$ be s.t.

i All high energy theories flow to the same subspace of $\mathcal{T}$—the subspace $\mathcal{T}^{eff}(\mu)$ of effective (at μ) theories.

ii This surface of attraction $\mathcal{T}^{eff}(\mu)$ is finite dimensional: finitely many couplings $g_i(\mu)$ suffice to specify an element of it.

?

“It is a remarkable property of local QFTs that . . . the low energy amplitudes can be parameterized by just a finite set of parameters—namely, those needed to locate the theory on the finite-dimensional attractive submanifold, and which can in principle be determined by making an equal number of independent experimental measurements.” (Duncan 2012, 587)



Polchinski 1984: For ϕ^4 theory, $\mathcal{T}^{eff}(\mu)$ is 3d and parameterized by the renormalized quantities ϕ_r, m_r, g_r the dippy process identifies.

Solving the Real Problem

The question: why should the approximation technique of perturbative renormalization work at all? What are the approximations approximations to?

The answer: higher energy elements of $\mathcal{T}$ that induce effective physics at scale μ.

They induce tractable effective theories because physics at scale μ requires only finitely many couplings to specify ($\mathcal{T}^{eff}(\mu)$ is finite dimensional). These couplings correspond to the finitely many coefficients reparameterized by perturbative renormalization schemes.

Despite not knowing the high energy details, we can completely specify the physics at scale μ by measuring the finitely many couplings that locate the effective theory in $\mathcal{T}^{eff}(\mu)$. We'll get the effective physics right even if our renormalization schemes are dicey.

Effective Realism

How to identify a locus of realist commitment not undermined by the Pessimistic MetaInduction:

> *Us[e] the RG to provide a means of identifying elements of Effective Field Theories that are invariant across independent and distinct choices about how to model the physics at the short distances [high energies] where the theory is empirically inapplicable. (Williams 2018, 11).*

- These "stable and robust" elements are going to survive no matter what the high energy physics is.
- Note! Effective Realism is local — it makes recommendations only about theories in the ambit of RG analyses.
- It is also judo-like: it turns underdetermination and agnosticism, standard empiricist weapons, into realist resources.
- Its advocates express suspicion of "Standard Interpretation."

The Suspect: Standard Interpretation

Standard Interpretation: "Whatever else it means to interpret a scientific theory, it means saying what the world would have to be like if the theory is true" (Earman 2004, 1234) . . .

Part of a quest for underlying ontology: "the goal of [standardly] interpreting a physical theory is to identify and characterize its fundamental ontological structure" (Williams 2018, 4)

An apparent questor:

> *Metaphysics is ontology. Ontology is the most generic study of what exists. Evidence for what exists, at least in the physical world, is provided solely by empirical research. Hence the proper object of most metaphysics is the careful analysis of our best scientific theories (and especially of fundamental physical theories) with the goal of determining what they imply about the constitution of the physical world. (Maudlin 2007, 104)*

Others: advocates of "naturalized metaphysics."

Against (Standard) Interpretation

Quark confinement: at high energy scales, the QCD Lagrangian $\mathcal{L}_{QCD}$ uses only quark and gluon degrees of freedom. Hadronic degrees of freedom (protons and neutrons) appear only in the effective Lagrangian induced for lower (atomic) energy scales.

A Standard Interpretation of QCD would articulate an ontology of quarks and gluons—and hamstring explanations of atomic behavior that rely on protons and neutrons.

> *It is a mistake to think that one can simply read a quantum field theory's ontology off its 'fundamental' mathematical structure. . . . The central vice of Standard Interpretation . . . is that it declares essentially all empirically applicable quantum field theories to be unfit for interpretation . . . An alternative response . . . is to conclude that it may be the approach to interpretation that is unfit for interpretive work, not the theory. (Williams 18, 11, 13; see also Hancox-Li 2015, J Fraser 2016, Miller 2017)*

(Faux Generality?)

Pessimism: T will be jettisoned in favor of (unknown) $T!$

Effective Realist response: no matter what $T!$ is, *these* features of T will be retained.

Gadfly: No matter what $T!$ is — provided it's in $\mathcal{T}$, supposing there's an explicit one at hand. But $\mathcal{T}$s could be so circumscribed that $T! \notin \mathcal{T}$ is a salient "skeptical" possibility. (If $T!$, then T isn't even approximately true. Near example of $T/T!$ pair: LUG and GR)

A dilemma for Effective Realism:

- if $\mathcal{T}$ is specified, the Pessimistic Metainduction retreats a level: skeptically relevant $T!$s $\notin \mathcal{T}$
- if $\mathcal{T}$ isn't specified, neither are the reassuring RG results

What does the ER endorse . . . ?

. . . that an empiricist wouldn't?

Effective Realism's criterion for commitment is robustness, as gauged by RG: that is, stability across variation in the underlying physics.

Some candidates for endorsement:

1. couplings parameterizing $T^{eff}(\mu)$. These are going to appear in the effective physics, no matter what the underlying physics is.
2. correlation functions ($\langle\hat{\phi}(x)\hat{\phi}(y)\rangle$) at effective scales (J Fraser 2018). The RG flow is defined to preserve these.

Each is ripe for harvest by the empiricist:

- The measurability of the couplings was key to solving the Real Problem.
- Correlation functions can be understood empirically, e.g. via LSZ reduction formula, as devices for calculating S-matrix elements and scattering cross-sections. (No appeal to Wightman reconstruction theorem until someone shows SM physics satisfies Wightman axioms.)

Effective Realist Commitments?

The Effective Realist can counter with an understanding of correlation functions $\langle\hat{\phi}(x)\hat{\phi}(y)\rangle$ less vulnerable to reduction— for instance as describing underlying processes such as "a photon of momentum k is created here while one of momentum k' is annihilated there."

[Irony?: Is this starting down the road of Standard Interpretation?]

The robustness criterion circumscribes commitments. But it neither

- articulates their content, nor
- defends them.

These leaves them vulnerable to empiricist appropriation.

Another Promising Candidate?

What does the Effective Realist endorse?

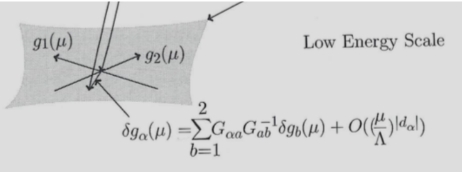
3. (Particles corresponding to) fields in the effective Lagrangian. Every Lagrangian in $\mathcal{T}^{eff}(\mu)$ incorporates the same list of fields ψ_i^{eff}. The roster of fields is robust.

Theory	fields at Λ	fields at μ
ϕ^4	scalar field	scalar field
Electroweak	W bosons, fermions	fermions
QCD	quarks, gluons	protons, neutrons

Endorsing the particles associated with these fields, Effective Realism undertakes commitments —e.g. to protons and neutrons! — apparently unpalatable to the empiricist.

Particle Puzzles: Relevance

ER: Where Lagrangians in $\mathcal{T}^{\mathit{eff}}(\mu)$ deploy fields ψ_i^{eff}, ψ_i^{eff} particles exist.



first puzzle: "relevance". Lagrangians in $\mathcal{T}^{\mathit{eff}}(\mu)$ deploy finitely many fields that make meaningful contributions to physics at scale μ. But they also deploy infinitely many other fields—fields whose contributions to correlation functions are suppressed by factors of $\frac{\mu}{\Lambda}$.

If Effective Realism endorses particles corresponding to all these fields, it's ontologically profligate.

If it confines endorsement to particles/fields that "contribute enough," it's offering a distinction of degree where we might have expected a distinction of kind (between what exists and what doesn't).

Particle puzzles: scale-dependence

Commitments circumscribed by the robustness criterion are scale-relative:

- what (relevant) fields/particles appear in $\mathcal{T}^{eff}(\mu)$ can depend on what μ is (quarks at QCD scale, hadrons at atomic scale);
- the roster of properties can depend on what μ is (color at QCD scale but not atomic scale);
- the values of intrinsic particle parameters can depend on what μ is (bare vs renormalized masses and charges);
- the symmetries of the effective Lagrangian can depend on what μ is.

The effective scale μ depends in turn on us and our limitations.

But ontology shouldn't.

Resolution

Puzzles: Effective Realism's commitments come in degrees and depend on our limitations—but ontology doesn't.

> *Any idea upon which we can ride . . . ; any idea that will carry us prosperously from any one part of our experience to any other part, linking things satisfactorily, working securely, saving labor; is true for just so much, true in so far forth, true instrumentally. (James 1907, 34)*

Both puzzles evaporate if the commitments circumscribed by RG considerations are understood not in terms of representational but in terms of pragmatic success: as commitments to utility for coping with phenomena at scale μ.

Utility comes in degrees (first puzzle) and manifestly depends on us and our limitations (second puzzle).

But understood in this way, commitments to fields/particles are commitments empiricists can live with.

Quasiparticles

The [electron] quasiparticle consists of the original real, individual particle, plus a cloud of disturbed neighbors. It behaves very much like an individual particle, except that it has an effective mass and a lifetime. But there also exist other kinds of fictitious particles in many-body systems, i.e. ‘collective excitations’. These do not center around individual particles, but instead involve collective, wavelike motion of *all* the particles in the system simultaneously. (Mattuck 1992,10)

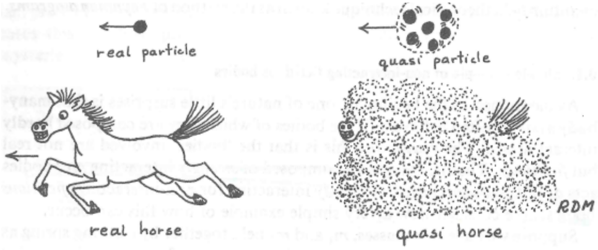


Fig. 0.4 *Quasi Particle Concept*

Quasi-ontology

Mattuck distinguishes between two sorts of quasiparticles.

- Some (like the dressed electron) which "consist of the original real, individual particle, plus a cloud of disturbed neighbors"
- Others (like the phonon) are fictitious—they aren't the particles constituting the system; they are useful devices for describing its collective excitations

Claim: the former are more deserving of ontological commitment.

Claim: distinguishing the former from the latter requires a lucid account of how they're realized in underlying ontology.

Claim: Effective Theories don't offer a lucid account of underlying ontology; Effective Realism counsels against extracting one from them.

Sneaky suspicion: To resist the "phononification" of their commitments, Effective Realists need to say more about how what they're committed to is related to underlying physics. (Liable to be something deflationary/revisionary about existence claims reconceived in terms of underlying physics: "there are hadrons" $\leftrightarrow$ "there are fundamental strings vibrating hadron-wise.")

A Peculiarity?

Effective Realists are dubious of Standard Interpretation. But they need something like an interpretation to present their commitments (which appear vulnerable to empiricist re-appropriation) as distinctively realist.

It's not Standard Interpretation Effective Realists should disavow. It's the explanatory uses to which fundamentalism would put Standard Interpretations.

Two questions about spectacularly successful T:

- i What does T say the world is like?; and
- e Why does T work as well as it does?

For the fundamentalist about T, answering [e] adequately requires answering [i]: T succeeds because the world is the way T says it is. A Standard Interpretation of T tells us what way that is. (Fundamentalist because no exogenous (to T) empirical considerations are required to explain T's success.)

Effective Interpretation

The fundamentalist: T succeeds because the world is the way T says it is. A Standard Interpretation of T tells us what way that is.

If T is an effective theory, fundamentalism botches the explanatory question. It's not the case that T succeeds because it is true fundamental theory $T!$. T succeeds because in experimentally-accessible regimes, T approximates $T!$'s predictions.

From the effective theory standpoint, fundamentalism goes wrong not by interpreting T but by incorporating T's interpretation into misguided and hubristic explanatory projects.

Two interpretive projects:

- si What must the world be like, if T is true?
- ei What must the world be like, that T succeeds as well as it does?

Effective Empiricism?

Good news for Effective Realism: Interpretation itself is consistent with the effective theory standpoint!

Not-so-good news: the price of its consistency is to sever the connection between T's truth and explanations of T's success—undermining abductive grounds for realism.

Another option: Effective Empiricism.

- The standard interpretive question can have a variety of answers that collectively promote properly scientific aims, such as theory development.
- Don't believe any single interpretation of T. Believe instead that T, when restricted to the limited domain, is empirically adequate.
- Steal the Effective Realist's explanation of T's success—it's impersonating $T!$ in a limited domain.

A more effective empiricism?

- Effective empiricists don't need to persuade anyone the universe is untidy. They entertain the possibility of a true and complete $T!$. What they question: how much T tells us about $T!$.
- Effective Empiricists offer an explanation of T's success—just not the one fundamentalists and realists favor.
- They thereby address the problem of selective skepticism. They use RG considerations both to limit the scope of T's capacity to save the phenomena and to explain why T will continue to exercise that capacity: no matter what $T!$ is, T is an accurate account of in-scope phenomena

Stirring Conclusion

1964: Wilfrid Sellars, "Scientific Realism or Irenic Instrumentalism." Options: Believe T, or don't take it literally.

1980: Bas van Fraassen, *The Scientific Image*. A new option! Take T literally, but don't believe it.

2010s: Effective Realists discover a fourth option: Believe T, but don't take it literally. Instead, believe . . . , where subjecting T to RG analysis helps fill in . . . .

Can this position be distinguished (invidiously!) from Effective Empiricism *without* traveling further down the path of offering literal interpretations *and* reasons to believe them?

Can Effective Empiricists and Effective Realists make common cause against Fundamentalists?