Renormalization Group Realism: The Ascent of Pessimism

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One realist response to the pessimistic meta-induction distinguishes idle theoretical wheels from aspects of successful theories we can expect to persist and espouses realism about the latter. Implementing the response requires a strategy for identifying the distinguished aspects. The strategy I will call renormalization group realism has the virtue of directly engaging the gears of our best current physics—perturbative quantum field theories. I argue that the strategy, rather than disarming the skeptical possibilities evinced by the pessimistic meta-induction, forces them to retreat a level. I also suggest that those skeptical possibilities continue to carry force.

1. Preliminary Fable. It's 1845, and we are trying to save phenomena involving planetary orbits. We have just the theory for the job. Its centerpiece is Newton's law of universal gravitation (LUG), whose inverse square force law subjects a planet of mass m orbiting a gravitational source of mass M at a distance r to the potential

$$V(r) = \frac{GMm}{r}, \tag{1}$$

where G is Newton's constant. Given the planet's kinetic energy, we can apply standard Lagrangian methods to solve exactly for the planet's orbit.

Our solution agrees well with observations. So elegantly and consiliently does our theory save this and other phenomena that we resolve to strike a stalwartly realist attitude toward it. We believe that LUG is (at least approximately) true and that its mechanisms and structures correspond to nature's deep and hidden springs, springs that act to bring about the phenomena the theory explains. These include forces acting at a distance across Euclidean

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three-space, understood as a time slice or instant of a 3 + 1–dimensional space-time whose isometries are given by the Galilean group.

Not everyone is ready to embrace LUG. One gadfly suggests a rival account: LUG is an approximation, valid for large orbits, to a potential arising from an inverse-cube correction to (1):

$$V_1(r) = \frac{GMm}{r}\left(1 + \frac{R_1}{r}\right). \tag{2}$$

Call this theory T_1. Another gadfly, somewhat lacking in originality, suggests that LUG is an approximation to a $1/r^4$ correction:

$$V_2(r) = \frac{GMm}{r}\left(1 + \frac{R_2^2}{r^2}\right). \tag{3}$$

Call this theory T_2. The couplings R_1 and R_2, the gadflies tell us, are to be determined by experiment. As if the gadflies are not annoying enough, an empiricist of our acquaintance invokes the availability of the rivals T_1 and T_2 to malign our favored theory as underdetermined by the phenomena it saves. Contending that this underdetermination undermines our warrant to believe LUG outright, this empiricist urges us instead to believe that LUG will continue to save the phenomena—a distinction it shares with its nearly empirically equivalent rivals—but to withhold belief from LUG's account of hidden springs and structures bringing these phenomena about. The question she raises is not is there a true story, call it theory *T*!, underlying these phenomena, but how reliable a guide is LUG to how that story goes?

We acknowledge that within their intended domains of application and within existing limits of observational accuracy, the theories are empirically equivalent. But we insist that LUG exhibits super-empirical virtues its unlovely rivals lack; for instance, it is simpler. We claim that these virtues warrant belief in LUG, notwithstanding the in-practice underdetermination dramatized by T_1 and T_2.

Alas, LUG is inconsistent with the data: equation (1) predicts no perihelion advance for any planet. But—LeVerrier has just announced—Mercury's perihelion advances 43 seconds of arc every century. Mercury is not alone in its failure to abide by LUG. Every planetary orbit exhibits perihelion advance.

While our favored theory cannot accommodate these data, its unlovely rivals can. With $R_1 = 4.4km$, (2) reproduces observed perihelion precession tolerably well. And with $R_2 = (p/m)/c$, where p is the planet's angular momentum and c is the speed of light, so does (3).[1] (Foreshadowing: Given this

1. See Wells (2015, chap. 1) for mathematical and historical details. The higher-order corrections (2) and (3) are examples of Clairault laws proposed to accommodate perihelion advance; $R_2 = (p/m)/c$ illustrates the velocity-dependent corrections Gerber introduced for the same purpose.

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expression for R_2, T_2 imposes a "correction" to Newtonian gravitation that becomes significant as p/mr approaches c in magnitude. But since the planetary angular momentum $p \sim mrv$, where v is the planet's velocity, this is just to say that T_2's correction predicts the breakdown of LUG as the planet's velocity approaches the speed of light.)

Although we are shaken by LUG's encounter with the shoals of perihelion advance, our realism need not be shipwrecked on those shoals. Recalling that realism about LUG commits us only to the theory's approximate truth, we cast LUG's failure to predict perihelion advance as a symptom of the difference between approximate and exact truth. Merely approximately true, LUG does not get every last detail right to every last decimal place. Approximately true, LUG will upon close examination exhibit minor blemishes. We resolve to regard perihelion advance as a cosmetic scratch on LUG's paint work.

Our empiricist is unsatisfied. She cavils: approximate truth is a conveniently vague notion we invoke to disavow commitment to theoretical features nature abjures, a notion whose contours realists set only in hindsight. Presciently, she levels the same complaint against other implements (structures, causal powers, etc.) by which future realists, enacting Psillos's *divide et impera* strategy, defend and refine their positions in response to the pessimistic meta-induction, the problem of unconceived alternatives, and the like. Until and unless we realists can say, without reference to the details of future theories, what we believe when we believe our favored current theories, our claims that those theories hold approximately, or get structure right, lack content.

We are not daunted. LUG posits an inverse square central force. Its rivals posit a central force that is dominantly $1/r^2$ in the vast majority of the regimes we investigate—regimes in which r is large. Its rivals are members of a family of theories correcting LUG by allowing higher orders of $1/r$ to make a physical difference as r approaches some characteristic length scale. A semigeneric example of a potential given by a theory in this family is

$$V_{ecu}(r) = \frac{GMm}{r}\left[1 + \sum_{n=1}^{\infty}\lambda_n\left(\frac{r_{0_n}}{r}\right)^n\right]. \tag{4}$$

The first term is just the LUG potential. Like that term, every other in (4) is Galilean invariant. (So are many other terms omitted by [4], such as terms in $\dot{r}$. Even more ecumenical expressions for the potential would incorporate such terms.) The term r_{0_n} is the length scale at which potential terms of order $(1/r)^n$ have a significant impact on physics. These length scales are presumably small compared to the orbital radii we care about. Barring untoward behaviors on the parts of the couplings λ_n, terms beyond the first look like they will not matter as long as r is large compared to the r_{0_n}'s.

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We can think of the family of potentials enumerated so far, along with every other appropriately symmetric potential, as forming a space $\mathcal{G}$ of theories taken to govern planetary orbits. What emboldens us to regard difficulties with perihelion advance as a sign that LUG is merely approximately true (in some duly specifiable sense) is that we take ourselves to be entitled to the following picture, announced in terms of complete, underlying theory T!:

> **[EFFECTIVE]**. No matter what the details of T! are, LUG is approximately true in these precise senses:
>
> i. We can characterize LUG's domain of applicability.
> ii. We can characterize those elements of LUG that are insensitive to (inevitably unknown, as long as we do not know T!) differences between LUG and T!. Put another way, we can characterize those elements of LUG that are invariant under changes in the physics that lies beyond LUG's grasp.

Clause i specifies the scope of LUG's approximate truth and clause ii the content of what we believe when we believe LUG to be approximately true.[2]

What entitles us to [EFFECTIVE] is a learned study high-powered friends have conducted of the space $\mathcal{G}$ of theories of planetary orbits.[3] The space $\mathcal{G}$ includes theories deploying the specific potentials discussed above, as well as those sharing their patterns of $(1/r)^n$ dependence but changing their couplings. Our learned friends have noticed that some theories in $\mathcal{G}$ can be regarded as siblings of a peculiar sort. Consider a theorist who is a bit sloppy and not very ambitious. He does not aspire to describe all planetary orbits or to describe any planetary orbit in fine detail. He wants to describe orbits in the domain ℓ of large orbital radii he cares about by a potential incorporating just a few orders of $1/r$ dependence. Another theorist is more persnickety and less modest. Her potential V^{Λ} treats a wider domain Λ of orbital phenomena and at many more orders of $1/r$ dependence than the sloppy theorist wants to deal with. The theory V^{Λ} also governs physics at the scale ℓ our sloppy theorist cares about.

Our learned friends' ground-breaking discovery is that the implications of this governance can be packed into coupling coefficients for (only a few) orders of $1/r$. The result is a potential V^{ℓ} that applies in the domain ℓ but en-

2. See Williams (2017) for a detailed account of how to use resources from effective theories to precisify and improve key realist claims

3. As far as I know, no one has developed the sort of renormalization group analysis of the space of higher-order corrections to LUG the fable imagines. The fable's pretense is for the sake of illustrating, in a setting less exotic than perturbative quantum field theories, the argument strategy of renormalization group realism.

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capsulates, via its couplings, implications for that domain of the underlying physics V^{Λ} describes. The theory V^{ℓ} is the effective (at scale ℓ) theory induced by the more fundamental theory V^{Λ}. Both are elements of $\mathcal{G}$, a generic element of which is a potential governing physics at a scale.

Our learned friends introduce a catchy name for the process of modifying coupling coefficients to reflect the implications for one scale of physics at underlying scales. They call it *renormalization*. And they introduce a gadget $R_{\mu\nu}$ on the space $\mathcal{G}$ of theories $\times$ scales that extracts from a relatively fundamental theory V^{ν} the effective (at scale μ) theory V^{μ} that underlying theory induces:

$$V^{\mu} = R_{\mu\nu}V^{\nu}.$$

With some violence to standard mathematical nomenclature, they call this gadget the *renormalization group* (RG) map.

We are ignorant of underlying physics. It is highly nontrivial, indeed practically a fantasy, that this ignorance in no way impedes our efforts to articulate physics adequate to phenomena within our grasp. But something like this fantasy, our learned friends tell us, holds of central force theories of gravitation. No matter what physics is missing from LUG, its impact in LUG's domain of application can be encapsulated by a finite number of corrections to LUG, coded by a finite number of renormalized couplings, whose values can be determined by experiment.

They know this, they tell us, because they have established that the renormalization group flow—the map $R_{\mu\nu}$ induces on the space $\mathcal{G}$—has surfaces of attraction. A finite-dimensional subspace of $\mathcal{G}^{\mu}_{\text{eff}} \subset \mathcal{G}$ is a surface of attraction at scale μ if and only if for all underlying scales ν and potentials $V^{\nu} \in \mathcal{G}$,

$$R_{\mu\nu}V^{\nu} \in \mathcal{G}^{\mu}_{\text{eff}}.$$

No matter which possible underlying theory in infinite-dimensional $\mathcal{G}$ you start with—no matter how many orders of $1/r$ it incorporates and via what couplings—that theory flows under the action of the RG group to the finite-dimensional subspace $\mathcal{G}^{\mu}_{\text{eff}}$ of effective (at scale μ) theories. This subspace is parameterized by the finitely many couplings $\{\lambda_i^*\}$ required to specify an element of it. This invariance of $\mathcal{G}^{\mu}_{\text{eff}}$ under the action of the RG signals that the full impact, on the physics we care about, of unknown physics is captured by the couplings $\{\lambda_i^*\}$. That they are finite in number means that we need to measure only finitely many variables to completely specify the renormalized theory, for instance, by determining what coefficient for the $1/r^2$ term in (2) saves the phenomena of perihelion advance.

Thus our justification of [EFFECTIVE] and, with it, our defense of a duly moderate and tempered realism about LUG. Identifying the domain (scale ℓ,

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say) in which LUG serves as an effective theory, RG analysis circumscribes the scope of our claim that LUG is approximately true. RG analysis also furnishes content for that claim. Thanks to invariants of the RG flow, RG analysis tells us what form the effective theory will adopt, no matter what the details of the underlying physics, and so tells us what features of LUG will survive the slings and arrows of theoretical progress. In our fable, these features include the central force form of the potential and Galilean invariance. To the extent that these features are preserved despite changes in the underlying physics, they are worthy candidates for realist commitment. RG analysis promises to help us identify components of our original and unreflective realism that survive both the affront of the pessimistic meta-induction and the realization that LUG is "merely effective."

This fable is prolegomenon. My official topic arises from outstanding work done recently—much of it by other contributors to this symposium—on the interacting quantum field theories (QFTs) occupying the tool kit of working physicists. That work embarks from a live problem in the foundations of physics: why do the oft-times desperate-seeming approximation techniques of perturbative QFT work as well as they do? To address this problem, it diagnoses interacting QFTs as merely effective and subjects them to RG analysis. This analysis inspires a new and precise strategy—*renormalization group realism*—for articulating a *divide et impera* realism adequate to the challenges posed by the pessimistic meta-induction. Sections 2–4, briefly and omitting much technical detail, will motivate and sketch RG realism.[4] Section 5 develops one criticism, inspired and reinforced by our preliminary fable, of the view. The criticism is meant to be friendly: I think that there is something deeply right about the attitude toward successful physics framing RG realism. I also think addressing initial concerns about an attitude is one way to develop its insights.

2. Perturbative QFT's "Real Problem." Many noninteracting (aka free) QFTs are well understood: the equations of motion determined by their Lagrangians are exactly soluble; we not only can produce their exact solutions but also use them to build Hilbert spaces and other arenas for quantum physics. Interacting QFTs are typically under less complete mathematical control: we cannot characterize precisely or directly the space of solutions to the equations of motion their Lagrangians determine. Perturbative approaches to interacting QFTs base an approximate account of those theories on our exact understanding of free theories to which they are closely related.

4. I will discuss a stock version of much subtler and thorough views presented in Fraser (2016) and Williams (2017). Wallace (2006) is an outstanding presentation of an attitude toward QFT foundations conditioning the view.

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The first step is to assume that the full Lagrangian of the interacting theory resolves into free and interacting parts. In the simplest case of a self-interacting mass m scalar field $\phi(x)$ living in two space-time dimensions,

$$L_0 + \lambda L_I = L(\phi, m, \lambda). \tag{5}$$

Here L_0 is the Lagrangian of the free theory ($\partial^2 + m^2$); the equations of motion it defines have exact solutions $\phi_0(x)$. The term L_I is the Lagrangian describing the field's self-interaction (ϕ^2 for a mass m scalar field interacting with itself via the potential $V(\phi) = \lambda\phi^4/4!$); the *coupling constant* λ is small to enforce the assumption that the interaction term modifies the free theory only slightly. Thus the full Lagrangian $L(\phi, m, \lambda)$ depends on the field, the mass, and the coupling.

The next step is to assume that solutions ϕ for the full theory take the form of a *perturbative expansion* around free solutions:

$$\phi(x) = \phi_0(x) + \lambda\phi_1(x) + \lambda^2\phi_2(x) + \cdots. \tag{6}$$

Now, we hope: if we can determine a few higher-order contributions $\phi_1(x)$, $\phi_2(x)$, . . . to this perturbative expansion, we can use the resulting approximation to calculate quantities of physical interest—n-point functions, S-matrix elements, and scattering cross sections—accurately enough to do empirical work.

Feynman diagrams are a tool for organizing and conducting such calculations. But following the Feynman rules, we encounter a hitch. Individual terms in the perturbative expansion diverge. For example, for the ϕ^4 self-interaction in four dimensions, integrals like

$$\int_0^\infty \frac{k^3}{k^2 + m^2}\, dk$$

(k momentum) crop up in these perturbative expansions. This integral diverges as momentum $k \to \infty$.

The standard fix for this ultraviolet divergence has two stages.[5] In the first stage, *regularization*, the problematic integral is rendered finite by refusing to integrate over all possible momentum modes. Instead, an ultraviolet cutoff Λ_{UV} is imposed:

$$\int_0^{\Lambda_{UV}} \frac{k^3}{k^2 + m^2}\, dk.$$

5. It is so called because high momentum corresponds to short (ultraviolet) wavelength. In QFT, there are also infrared divergences and—supposing individual terms in the perturbative expansion could be rendered finite—the question of whether the infinite sum (6) converges.

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Now the integral is finite, but our theory has a new embarrassment. It is cutoff-dependent: the quantities it generates are sensitive to the value of the cutoff Λ_{UV} we use. But physics should not depend on arbitrary features of our calculation techniques!

The next stage of the fix, *renormalization*, alleviates this embarrassment. By artful manipulation of counterterms and crafty cascades of cancellations, we rewrite the original Lagrangian using new coefficients cleverly chosen so that as $\Lambda_{UV} \to \infty$, terms in the perturbative expansion at each order converge in such a way that their cutoff dependence disappears. For the ϕ^4 theory, the result of renormalization is to replace the "bare" field ϕ, bare mass m, and bare coupling λ parameterizing the original Lagrangian with renormalized counterparts ϕ_r, m_r, λ_r. The renormalized Lagrangian results.

In general, renormalized Lagrangians may feature fields additional to (and not just renormalized versions of) fields in the original Lagrangian. As long as the renormalized Lagrangian contains only finitely many terms (i.e., can be obtained by way of only finitely many reparameterizations), the physics it defines is humanly tractable, and the theory is said to be *perturbatively renormalizable*.

In practice, the precise values of the renormalized masses and couplings are not supplied by calculations mediated by specific (and possibly inapt) renormalization schemes. They are determined experimentally. Once these parameters are supplied, perturbatively renormalized QFTs enjoy stunning predictive success. Gawedzki aptly conveys the sense of wonder/suspicion the saga of perturbative renormalization evoked in those who witnessed it: "There exists a celebrated procedure, called *renormalization*, which removes the short distance divergences from the field theoretic Perturbative Expansion. 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" (1986, 1279–80). The spectacular agreement prompts what James Fraser has called perturbative QFT's "real problem." Given a QFT whose perturbative treatment can be domesticated by the standard grab bag of divergence-taming techniques and whose resulting predictions are upheld, we confront a foundational question: why do these techniques work as well as they do? Put another way, what are perturbative approximations approximations to? Perturbative QFT itself gives us no guidance. "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. . . . [This] undercuts the possibility of telling a physical story which could explain its success" (Fraser 2017, 17–18).

3. Renormalization Group Resolution. Perturbative QFT's real problem is that it offers us no guidance toward a physical picture that explains its

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success. Renormalization group considerations underwrite a solution (Wallace 2006; Hancox-Li 2015; Fraser 2016; Williams 2017). The solution's crux is to reject an assumption expressive of a sort of fundamentalism about theories. This is the assumption that resources endogenous to a theory T are sufficient to explain T's empirical success. A rival possibility, made vivid by the very idea of an effective theory, is that T succeeds as well as it does not because on its own it delivers a complete and accurate picture of physical reality but because, whatever the complete and accurate picture of physical reality is, T approximates its deliverances for phenomena in T's domain of application. That is, T succeeds not because it is complete fundamental theory T! but because it mimics T! in regimes we investigate.

To entertain the possibility that perturbative QFTs are effective theories is not to explain their success in a way that engages the gears of perturbative approximation techniques. RG analyses help fill these lacunae. Consider a space $\mathcal{T}$ of QFT Lagrangians $\times$ scales (at which predictions extracted from those Lagrangians apply). Each Lagrangian is a multinomial of a (possibly infinite) collection of fields and their space-time derivatives, with coefficients supplied by masses and couplings. The scale ℓ, experimentally accessible to us and in the scope of our perturbatively renormalized QFT Q, is low energy. Underlying theories govern phenomena at higher energies. Now suppose that on $\mathcal{T}$ is defined an RG flow with some highly suggestive features. For scale ℓ, this RG flow identifies a finite-dimensional surface of attraction $\mathcal{T}^{\ell}_{\text{eff}}$; $\mathcal{T}^{\ell}_{\text{eff}}$ has as many dimensions as Q's perturbatively renormalized Lagrangian has terms. Different elements of $\mathcal{T}^{\ell}_{\text{eff}}$ differ in the coefficients modifying those terms. The renormalized masses and couplings defining Q's renormalized Lagrangian thus also define an element of $\mathcal{T}^{\ell}_{\text{eff}}$.

With this picture in view, we can posit that Q succeeds as well as it does because no matter what the details of higher-energy physics, its implications for physics at accessible scale ℓ are encapsulated by theories in the surface of attraction $\mathcal{T}^{\ell}_{\text{eff}}$ to which all higher-energy theories flow under the action of the RG group. Our low-energy theory Q corresponds to one of these theories—the very one identified by experimental determinations of the variables parameterizing $\mathcal{T}^{\ell}_{\text{eff}}$, the renormalized masses, and couplings that define Q's perturbatively renormalized Lagrangian.

Duncan summarizes the RG explanation of perturbatively renormalized Q's empirical success: "It is a remarkable property of local QFTs that for a certain subset of theories, . . . 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" (2012, 587).

But is it wishful thinking to count on the "remarkable property" on which this solution to the real problem rests? Polchinski (1984) establishes a result

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suggesting that it is not. He considers a space of theories $\mathcal{T}$ consisting of Lagrangians that are polynomials in a four-dimensional scalar field and its derivatives and that take the form of the free Klein-Gordon field with weakly coupled interactions. He defines the RG flow as that map on the space of theories that preserves n-point functions: restricted to the effective scale, the underlying theory and its image under the RG map, when subject to the Feynman rules, determine the same set of n-point functions. The motivation for this requirement is that agreement about n-point functions is sufficient for theories to agree in empirical content.

Polchinski's result is that under the action of this RG flow, $\mathcal{T}$ has a three-dimensional surface of attraction, where this surface is parameterized by couplings m^* (the effective mass), λ^* (the effective coupling), and ϕ^* (the effective field).[6] Effective theories in this surface include the perturbatively renormalized ϕ^4 Lagrangian we know and love! This is an explicit demonstration that at least one perturbatively renormalizable QFT lives in a space of theories exhibiting the remarkable property underlying the RG resolution of perturbative QFT's real problem.[7]

4. Renormalization Group Realism. Why should the approximation technique of perturbative renormalization work at all? What are the approximations approximations to? The answer suggested by RG analyses is that perturbatively renormalizable interacting QFTs, astonishingly successful at applications to experimentally accessible regimes, are approximations to higher-energy elements of $\mathcal{T}$ furnishing the physics underlying physics at (experimentally accessible) scale ℓ. This underlying physics induces tractable effective theories because physics at scale ℓ requires only finitely many renormalized parameters to specify; that is, $\mathcal{T}^{\ell}_{\text{eff}}$ is finite-dimensional. Despite not knowing the high-energy details, we can completely specify the physics at scale ℓ by measuring the finitely many couplings that locate the effective theory in $\mathcal{T}^{\ell}_{\text{eff}}$. We will get the effective physics right even if our infinity-taming cutoff procedures are dicey.

One strategy by which the realist might respond to the pessimistic meta-induction is *divide et impera*: distinguish aspects of our best current theories we can reasonably expect to persist in the face of theory change from idle theoretical wheels and espouse realism about the distinguished aspects. The

6. More precisely, all but three terms in the effective Lagrangian become irrelevant, where "irrelevant" means (roughly) having negligible effect on the n-point functions calculated using the effective Lagrangian.

7. Noting that there is no a priori reason to expect susceptibility to domestication by standard perturbative renormalization techniques to be either necessary or sufficient for the "remarkable property" to obtain, here is another way RG analysis figures significantly in the project of modern physics: it can make nonperturbatively renormalizable theories tractable!

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solution just sketched to the foundational puzzle about perturbative renormalization techniques suggests a tolerably precise *divide et impera* strategy.

This strategy, which I will call renormalization group realism, applies to empirically successful effective theories in the ambit of RG techniques. It opens by acknowledging those theories to be merely effective. That is, they succeed at experimentally accessible low-energy scales because they approximate the implications higher-energy physics (at present unknown) holds for phenomena at those scales. The strategy next appeals to RG considerations to identify features of these effective theories that are robust under variations in the underlying, unknown higher-energy physics. The criterion of robustness is "invariance under the RG flow"—understood as a signature of lower-energy physics insensitive to the details of physics at higher-energy scales. Porter Williams identifies the hope on which RG realism rests: "both the renormalization group and attention to applications can be employed to distinguish mathematical elements of the theory that have a genuinely representational role—those which have genuine physical content—from those which are mere mathematical artifacts" (2017, 3).[8] The former "play an essential or 'active' role in the theory's empirical success" and are "stable and 'robust'"; as such they "can be expected to survive future episodes of theory change" (14). Features invariant under the RG flow are fodder for a *divide et impera* realism resistant to the pessimistic meta-induction.

5. Conclusion: The Ascent of Pessimism. To identify, in spite of our ignorance, aspects of current theories that represent the way the world is, RG realism offers the "robustness" criterion:

> What is invariant under action of RG group/insensitive to choice of cutoff is real (at scale ℓ).

It invokes RG considerations to assure us that these invariants are going to survive (as elements of physics at scale ℓ) no matter what the high-energy physics is. This section suggests that the assurance is compromised by a certain faux generality afflicting RG analyses.

Consider a skeptic about theory T's capacity to represent the way the world is. Evoking our old friend, the unknown, fundamental theory T!, she might justify her skepticism by claiming we have no grounds for taking T's representations as a guide to T!'s representations. The RG realist re-

8. One respect in which the stock version of RG realism I consider here differs from Williams's view is that the stock version pays little "attention to applications." A key question, bracketed here because of space limitations, is how such attention should inform the view.

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sponds: no matter what $T!$ is, these features of T—the ones robust under the RG—will be retained! So these features are reliable guides to $T!$/the way the world is. The skeptic hesitates. The RG realist's conclusion holds no matter what $T!$ is, provided that it is in the space $\mathcal{T}$ on which the RG acts, supposing there is an explicit such space at hand. But $\mathcal{T}$ could be so circumscribed that $T!$ lying outside it is a salient "skeptical" possibility, in the sense that if $T!$, then T is not a reliable guide to how the physical world is.

The skeptic presses a dilemma upon the RG realist. Either the space of theories $\mathcal{T}$ on which the RG acts is explicitly specified or it isn't. If $\mathcal{T}$ is specified, the pessimistic meta-induction retreats a level: skeptically relevant $T!$s $\notin \mathcal{T}$ undermine grounds for belief in T's representational success. If, on the other hand, $\mathcal{T}$ is not specified, neither are reassuring RG results about which features of T are invariant under the details of the underlying physics.

Existing RG results do make use of avowedly circumscribed spaces of underlying theories. Mathematical physicists recognize that the circumscription reflects choices that may omit crucially relevant possibilities:

> Needless to say that we do not know how to solve [the RG equation] in general. *Some approximations are thus required*. . . . The strategy consists in *solving the RG equation in a restricted functional space* and not as a series expansion in a small parameter. This is why we can hope to obtain nonperturbative results. . . . Of course, *the quality of the result will depend crucially on the choice of space* in which we search for a solution. . . . In all cases, *it is impossible to know whether we have missed some physically crucial ingredient by making one choice rather than another one*. (Delamotte 2007; italics mine)[9]

> The arguments given here [Polchinski's], based as they are on a linear stability analysis, *make sense only in the context of perturbation theory*, where we are entitled to treat all couplings associated with interaction operators as infinitesimal. . . . *No statement is made—nor can be made—concerning the actual existence of flows beginning at the specified UV starting point . . . with* finite *rather than infinitesimal couplings*. . . . This is a global issue which requires non-perturbative control over the theory. (Duncan 2012, 658; italics mine)

The concern is that even explicit RG results are only as reassuring as the space of theories on which the RG group acts is comprehensive. But that

9. "But this problem is not specific to the Non-Perturbative Renormalization Group. It is generic in physics," he continues. Whether you consider this grounds for dismissing the skeptical worry or for universalizing it probably amounts to some sort of philosophical Rorschach test.

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space incorporates assumptions about what kinds of interactions are possible and how to model them. And nature is not beholden to respect those assumptions.

Our opening fable illustrates the epistemic dangers of overconfidence in the comprehensiveness of a theoretical space. There, reflection on the space $\mathcal{G}$ containing LUG and perturbative corrections thereto inspired the fable's realist heroes to hope: no matter what the details of underlying fundamental physics, its implications for physics at orbital radii we care about can be captured by a finite number of small empirically tractable corrections to LUG. In this sense, LUG is approximately true, and we can with confidence subscribe to those aspects of LUG stable under the corrections necessary to accommodate physics involving higher orders of $1/r$. These include central gravitational forces acting instantaneously at a distance across Euclidean three-space.

From the standpoint of present physics, our heroes' confidence is misplaced. The perspective of general relativity (GR) supports a starkly different commentary on LUG as an effective theory. The equations of motion determined by the cubic correction to LUG are low-velocity, low-eccentricity, large-radius limits of the equations of motion arising from the Schwarzschild solution of the field equations of GR. GR does away with central forces acting instantaneously across Euclidean space. Reassuring considerations of features it shares with an apparently encompassing and empirically accommodating space of theories notwithstanding, LUG gets the hidden springs dead wrong. Reflection on $\mathcal{G}$ assured us that aspects of LUG will persist in empirically adequate accounts of orbital phenomena throughout the incorporation of higher and higher orders of $1/r$ dependence in descriptions of those phenomena. Taking those aspects to represent how the world is, we would have been led astray.

The fable dramatizes the worry developed here about RG realism. RG considerations make a compelling case for a certain sort of theoretical resourcefulness: the resourcefulness effective theories exhibit when they sequester our physical ignorance in a few couplings summarizing the implications of what we do not know for the phenomena we deal with. Such resourcefulness is consistent with profound ignorance: theories trafficking in fields acting on four-dimensional space-time could define physics perfectly effective at mortally accessible scales in a universe that is fundamentally stringy and 26-dimensional. In such a universe, we can base an ontology on aspects of effective field theories invariant under the action of the RG on a space of four-dimensional field theories. And we would have excellent reason to use that ontology to design experiments, form expectations, and offer explanations. That is, we would have excellent reasons to adopt toward that ontology the attitude recommended by empiricists who recognize the scientific value of taking theories literally. To be realists about the effective

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theory, however, we need to do something more. We need to believe the ontology, where there is more to belief than the empiricist commitment just described. That something more should not be: the ontology accurately represents how the world is. In this scenario, the world is 26-dimensional and stringy; the ontology represents as four-dimensional and fieldy.

The possibility that *T*! lies far outside the spaces to which RG analyses apply underscores a question for RG realism: what commitments does it defend and endorse that distinguishes it from empiricism?

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