Why Students Deserve More Than One Theory of Gravity: Underdetermination and the Pedagogy of Modern Physics

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Abstract

The underdetermination of theory by data is one of the most established principles in the philosophy of science. Yet modern physics education proceeds as though underdetermination does not exist. Graduate students learn General Relativity as the singular correct description of gravity, largely unaware that multiple alternative frameworks—built on entirely different ontological foundations—reproduce the same classical predictions to identical precision. This paper examines the pedagogical consequences of this omission. Drawing on the Duhem-Quine thesis, Lakatos's methodology of research programmes, historical case studies from the Copernican revolution, and contemporary sociology of scientific institutions (Latour, Bloor), we argue that the systematic exclusion of viable alternative ontologies from physics curricula constitutes a form of epistemic negligence. We propose the integration of computational model-comparison exercises into graduate education as a practical remedy, and we examine the institutional incentive structures that sustain the current monoculture.

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1. A Parable from Psychology

Imagine a graduate program in clinical psychology where the entire curriculum consists of Sigmund Freud. The students read Freud. They discuss Freud. They write dissertations applying Freud. When they encounter a patient exhibiting anxiety, they reach for the Oedipal complex. When they encounter depression, they reach for repressed childhood trauma. They do this not because they have carefully weighed the Freudian model against its competitors—cognitive-behavioral therapy, attachment theory, humanistic psychology, neurobiological models—but because they have never been told that competitors exist.

No serious psychology department operates this way. The field learned, painfully and over decades, that theoretical pluralism is not a sign of weakness but a prerequisite for intellectual maturity. A clinician trained in multiple paradigms is not confused; they are *equipped*. They can recognize when one framework illuminates a case and another obscures it. They can hold competing explanations in productive tension.

Physics, remarkably, has not yet learned this lesson.

In the domain of gravitational physics, the situation is structurally identical to our hypothetical psychology department. The evidence is not anecdotal. A survey of publicly available graduate curricula at leading institutions confirms the pattern: MIT's General Relativity course (8.962), Caltech's Applications of Classical Physics (Ph 136), and Cambridge's Part III course on General Relativity each teach gravitational physics entirely within the framework of Einstein's field equations. Alternative gravitational ontologies—theories that reproduce the same empirical predictions from different foundational assumptions—do not appear in any of these syllabi. The pattern is representative, not exceptional. Graduate students are trained almost exclusively within the framework of General Relativity. They learn to solve Einstein's field equations. They learn the Schwarzschild metric, the Kerr metric, the Friedmann-Lemaître-Robertson-Walker cosmology. What they almost never learn is that the empirical predictions they have been calculating—the perihelion precession of Mercury, the deflection of starlight, the gravitational redshift measured by GPS satellites—can be derived with equal precision from theories that assume a fundamentally different picture of reality.

This is not a minor pedagogical detail. It is, we shall argue, an epistemic failure with far-reaching consequences.

2. The Duhem-Quine Thesis and Its Forgotten Implications

The philosophical foundations for our argument were laid more than a century ago. Pierre Duhem, in *The Aim and Structure of Physical Theory* (1906), demonstrated that no single hypothesis can be tested in isolation; every empirical test involves an entire web of auxiliary assumptions. W. V. O. Quine extended this insight in *Two Dogmas of Empiricism* (1951), arguing that any body of empirical evidence is compatible, in principle, with multiple theoretical frameworks.

This is the thesis of *underdetermination*: the data alone cannot uniquely determine the theory.

In philosophy departments, underdetermination is taught in introductory courses. Students encounter it alongside discussions of Popper, Kuhn, Lakatos, and Feyerabend. They learn to think critically about the relationship between evidence and theory, between mathematical structure and physical reality.

In physics departments, underdetermination is largely invisible. The implicit pedagogical message is that the mathematical formalism of General Relativity does not merely *predict* the behavior of gravity—it *is* the behavior of gravity. Curved four-dimensional spacetime is not presented as a model; it is presented as a discovery about the nature of reality itself.

This conflation of predictive success with ontological truth is precisely what the Duhem-Quine thesis warns against. And in gravitational physics, the warning is not abstract: concrete alternative theories exist, they work, and they tell very different stories about what the universe is made of.

3. Why General Relativity Dominates—And Why That Is Not Enough

Before examining alternatives, it is important to acknowledge why General Relativity occupies the central position it does. GR is not dominant by accident or by conspiracy. It is dominant because it is extraordinarily good. It unified gravity and inertia into a single geometric framework. It predicted gravitational waves decades before they were detected. It provided the theoretical foundation for modern cosmology, black hole physics, and precision satellite navigation. Its mathematical structure—Riemannian geometry applied to a pseudo-Riemannian manifold—possesses an internal elegance that is rare in the history of physics. Many serious physicists regard the teaching of alternatives as a distraction precisely because GR has passed every experimental test with remarkable precision, and because no alternative has demonstrated clear empirical superiority.

These are legitimate considerations. The argument of this paper is not that GR should be displaced from its central pedagogical role. It is that pedagogical centrality should not mean pedagogical exclusivity. The difference matters, because the philosophy of science reveals a structural gap between "passes every test" and "is the only possible explanation"—a gap that students are rarely taught to recognize.

The strongest version of the objection is the pragmatic one: if all viable alternatives yield the same numbers, then teaching them is a waste of finite curricular time. This argument deserves a direct answer. It fails for three reasons. First, it confuses the current state of empirical equivalence with a permanent one; the history of science shows repeatedly—Copernicus and Ptolemy, Lorentz and Einstein, wave and matrix mechanics—that ontological alternatives which appear empirically degenerate at one scale of measurement diverge decisively at the next. Second, it underestimates the cognitive value of contrast: a student who has derived the same perihelion precession from two incompatible ontologies understands the physics more deeply than one who has derived it from only one, because they can now distinguish which features of the result depend on the data and which depend on the formalism. Third, it ignores the institutional cost of monoculture documented in Sections 6 and 7: when an entire generation is trained to think in only one ontological vocabulary, the community loses its capacity to recognize anomalies as signals rather than noise.

4. The Landscape of Predictive Equivalents: Structure, Not Catalogue

In the Parameterized Post-Newtonian (PPN) formalism, any gravitational theory that correctly reproduces the classical Solar System tests must yield the parameters $\gamma = 1$ and $\beta = 1$. General Relativity satisfies this constraint. But it is far from alone.

What makes this landscape philosophically significant is not merely the *number* of alternatives, but the *depth of their disagreement*. These are not minor variations on a theme. They disagree about the most basic ontological questions in physics: Is space curved or flat? Is gravity a geometric property of spacetime or a force propagated through a medium? Is the gravitational constant truly constant?

Consider three distinct categories of disagreement:

Ontological disagreement about the nature of space itself. General Relativity (Einstein, 1915) describes gravity as the geometric curvature of a four-dimensional spacetime manifold. The Teleparallel Equivalent of General Relativity, or TEGR (also formulated by Einstein, in 1928), produces mathematically identical predictions but attributes gravitational effects entirely to the *torsion* of a flat spacetime. Space, in this framework, is not curved at all. The two theories are empirically indistinguishable at the level of every currently feasible experiment, yet they disagree about something as fundamental as whether space is curved or flat.

This single example should give every physics educator pause. If two frameworks, both originating from Einstein himself, produce identical empirical predictions while disagreeing about the geometry of space, then the geometrical interpretation of gravity is, at least in part, underdetermined by the available empirical evidence.

Ontological disagreement about the constancy of physical laws. Brans-Dicke theory (Brans and Dicke, 1961) introduces a scalar field that makes the gravitational constant vary across space and time. It reproduces all classical Solar System tests when its coupling parameter ω exceeds approximately 40,000—a constraint comfortably satisfied by current observational bounds. Here the disagreement is not about geometry but about whether the "constants" of nature are truly constant. A student trained only in GR never encounters this question.

Ontological disagreement about the medium of gravity. A third class of theories dispenses with curved spacetime entirely and models gravity as a phenomenon occurring in flat three-dimensional Euclidean space. In these frameworks—including historical models and more recent constructions such as Euclidean Field Relativity—the vacuum is treated not as empty curved geometry but as a medium with variable optical properties. Gravitational effects (light deflection, time dilation, orbital precession) emerge from classical wave mechanics applied to this medium. The numbers match. The ontology is radically different.

The point is not that any one of these alternatives is "correct" and General Relativity is "wrong." The point is that the empirical data—the numbers that students calculate in their problem sets—do not distinguish between these ontologies. The choice of ontology is underdetermined by the data. And students who are never told this are being given a deeply incomplete education.

5. Historical Precedent: Copernicus, Ptolemy, and the Ontological Leap

The history of science offers a powerful precedent for the situation we describe. When Copernicus proposed his heliocentric model in 1543, his mathematics was not more accurate than the geocentric model of Ptolemy. The two systems were, in many respects, empirically equivalent. Both could predict planetary positions. Both could account for retrograde motion.

The advantage of the Copernican model was not in its data. It was in its *ontology*. By placing the Sun at the center, Copernicus created a conceptual framework that later allowed Kepler to discover elliptical orbits and Newton to formulate the law of universal gravitation. The geocentric model, despite its mathematical adequacy, was an ontological dead end. Its epicycles could be endlessly refined, but they led nowhere new.

The lesson is direct and uncomfortable: a theory can be mathematically adequate and ontologically sterile. It can fit every available data point and still block future progress, simply because it tells the wrong story about what is happening.

If Ptolemaic astronomy had been taught as the *only* valid framework, and if students questioning its ontology had been discouraged, Kepler's laws might have been delayed by centuries. The parallel to modern gravitational physics is not exact—it never is—but the structural similarity is worth taking seriously.

6. Modern Epicycles and the Cost of Ontological Rigidity

The Copernican precedent acquires contemporary urgency when we examine how the physics community responds to anomalous data within the current paradigm.

When a dominant framework encounters observations it cannot explain, two responses are possible. The first is to question the underlying ontological assumptions. The second is to preserve the ontology and introduce auxiliary entities to absorb the anomaly.

Imre Lakatos, in *The Methodology of Scientific Research Programmes* (1978), described this second response as the expansion of a theory's "protective belt"—a process that can be either progressive (leading to novel predictions) or degenerative (merely accommodating known anomalies without generating new testable content).

General Relativity, when applied to galactic and cosmological scales without additional components, does not account for observed rotation curves of galaxies or the accelerating expansion of the universe. Rather than investigating whether the ontological assumptions of GR might be inadequate at these scales, the predominant response has been to introduce two new entities: dark matter and dark energy. Together, these entities constitute approximately 95% of the total mass-energy content of the universe. Neither has been directly detected despite decades of dedicated experimental effort.

We do not claim that dark matter and dark energy are necessarily wrong. They may exist. What we do claim is that a student educated exclusively within the GR paradigm has no basis for evaluating whether these entities represent genuine physical discoveries or whether they function as auxiliary hypotheses—mathematical devices that preserve a particular ontological commitment.

A student who knows that MOND-based theories (such as TeVeS, formulated by Bekenstein in 2004) can explain galactic rotation without dark matter is better equipped to evaluate the evidence. A student who knows that f(R) gravity (Buchdahl, 1970; with chameleon screening by Khoury and Weltman, 2004) can modify cosmic expansion without dark energy has a broader perspective. A student who knows none of this is not doing physics in the fullest sense. They are performing calculations within a single approved framework, unable to assess its boundaries.

7. The Institutional Economy of Monoculture

The persistence of pedagogical monoculture in physics is not merely a matter of intellectual inertia. It is sustained by concrete institutional and economic incentive structures.

Bruno Latour, in *Science in Action* (1987), described the process by which scientific facts become "black-boxed"—accepted as settled, their contingent origins forgotten, their alternatives rendered invisible. David Bloor's *Strong Programme* in the sociology of scientific knowledge (1976) argued that the social organization of scientific communities shapes which ideas are pursued and which are marginalized, independently of their empirical merits. Thomas Kuhn's concept of "normal science" (1962) describes precisely the pattern we observe: a community of researchers working within a shared paradigm, solving puzzles defined by that paradigm, and treating challenges to the paradigm's foundations as illegitimate.

These are not marginal perspectives. They represent some of the most influential analyses of how science actually operates, as opposed to how it idealizes itself.

In contemporary physics, research funding is allocated through peer-review committees composed of established researchers—individuals who have built their careers, their reputations, and their publication records within the dominant paradigm. This creates a structural incentive asymmetry. It is exceedingly difficult to secure funding for research programs that investigate alternative gravitational ontologies, while immense resources are continuously allocated to increasingly large underground detectors (LUX, XENON, PandaX) searching for dark matter particles that have, to date, eluded detection.

The consequences for young researchers are substantiated by decades of research in the sociology of science. Robert K. Merton, in *The Sociology of Science* (1973), identified the "Matthew Effect"—the systematic tendency of established scientists and established paradigms to accumulate disproportionate resources and

recognition, while newcomers and heterodox programs are marginalized. Harriet Zuckerman's study of Nobel laureates (*Scientific Elite*, 1977) documented how elite networks within science concentrate intellectual and material capital, reinforcing dominant research programs. Edward Hackett (1990) examined how the structure of research funding distorts scientific priorities, rewarding safe, paradigm-consistent proposals over exploratory or heterodox ones. Taken together, these analyses suggest that research programs outside dominant paradigms consistently face higher publication and funding barriers—not because they lack empirical merit, but because the institutional machinery is structurally biased toward continuity.

For a graduate student, the message is unambiguous: pursue alternatives at your own risk. The result is a pervasive culture of self-censorship, in which heterodox ideas are abandoned not because they fail empirically, but because pursuing them is perceived as professionally hazardous.

This is not a conspiracy. It is an emergent property of a system that rewards conformity and penalizes deviation. But the pedagogical consequences are severe. Students learn not only a particular theory of gravity; they learn that questioning it is impractical, unfunded, and socially costly. The monoculture reproduces itself not through argument, but through economics.

8. A Pedagogical Proposal: Computational Sandboxes for Ontological Pluralism

If the problem is a failure to teach alternatives, the remedy must be practical. Abstract lectures on the philosophy of underdetermination, however valuable, are unlikely to change deeply ingrained habits of thought. Students need to *experience* ontological pluralism directly, not merely hear about it.

We propose the integration of open-source computational sandboxes into graduate physics curricula. These are software environments in which students can solve the same physical problem using multiple theoretical frameworks, side by side, and compare the numerical results. The pedagogical objective is not to convince students that any particular alternative is superior to General Relativity. It is to demonstrate, concretely and unmistakably, that the same empirical data can emerge from radically different ontological assumptions.

Example 1: The Orbit of Mercury. A student computes the perihelion precession of Mercury using the geodesic equations of the Schwarzschild metric in curved spacetime. They obtain 42.98 arcseconds per century. Then, using the same software environment, they switch to a flat-space model in which gravitational effects arise from a refractive gradient in a continuous medium. They obtain the same 42.98 arcseconds per century. The numbers are identical. The underlying physical story is completely different. In one model, a planet follows the curvature of spacetime. In the other, it follows a density gradient in a flat medium. The student is now equipped to ask: which story does the data actually support? Or does the data support both equally?

Example 2: The Bond Angle of Methane. To demonstrate that ontological pluralism extends beyond gravitational physics, the same computational approach can be applied to molecular structure. A student calculates the 109.5-degree bond angle of methane using the standard formalism of quantum orbital hybridization (sp^3 mixing of atomic orbitals). Then they recalculate the same angle by minimizing classical fluid-mechanical stress in a continuous medium model. Both approaches converge on 109.5 degrees. The student discovers that even at the molecular scale, predictive equivalence between quantum and classical ontologies is not merely hypothetical—it is computationally demonstrable.

Example 3: Gravitational Time Dilation. A student derives the frequency shift of a GPS satellite clock using the Schwarzschild solution of General Relativity. Then they derive the same shift using a variable refractive index in flat Euclidean space, where "time dilation" emerges as a consequence of wave propagation speed varying with medium density. The numerical agreement is exact. The ontological implications are opposite: one framework requires time itself to flow at different rates; the other requires only that wave speed varies in a medium.

When students see, on their own screens, that the cosmos, the molecule, and the satellite clock can all be accurately modeled by entirely different ontological assumptions, the philosophical point ceases to be abstract. It becomes immediate. They understand, in a way that no lecture can convey, that the mathematical formalism is a tool for organizing predictions—not a window into the ultimate structure of reality.

The computational infrastructure required for such exercises largely exists, but has not been organized for pedagogical use. Thousands of open-source projects simulate orbital mechanics, molecular geometry, and wave propagation; general-purpose symbolic computation environments (such as SymPy and SageMath) can derive the relevant equations in any formalism. What does not yet exist at scale is a curated, classroom-ready environment that places these derivations side by side and invites structured comparison. Building such environments is a tractable engineering problem, not a research frontier. What is needed is not new technology, but a willingness on the part of physics departments to commission and adopt comparative ontological exercises.

A note on positionality is warranted here. The author has developed one such computational framework (Euclidean Field Relativity, implemented in the RAKTS simulation package). This creates an inherent tension: the argument for pedagogical pluralism is advanced by someone who stands to benefit from its adoption. The reader should weigh this accordingly. The argument of this paper, however, rests entirely on the philosophical principle of underdetermination—a principle that holds regardless of whether any particular alternative framework, including the author's, proves durable.

9. Conclusion: A Vaccine Against Dogmatism

The argument of this paper is simple but, we believe, consequential. Modern physics education systematically deprives students of knowledge about viable alternative theories—theories that reproduce the same empirical predictions as General Relativity while resting on fundamentally different ontological foundations. This omission has pedagogical, institutional, and scientific consequences.

Pedagogically, it produces physicists who cannot distinguish between mathematical adequacy and ontological truth. Institutionally, it creates a self-reinforcing monoculture sustained by funding structures and publication norms. Scientifically, it risks repeating the pattern Kuhn identified in *The Structure of Scientific Revolutions*: the indefinite accumulation of auxiliary hypotheses around a paradigm that may be ontologically misleading, blocking the conceptual breakthroughs that a shift in perspective might enable.

We do not argue that General Relativity should be displaced. Its mathematical elegance and predictive power are extraordinary, and its central place in the curriculum is fully deserved. We argue that it should be *contextualized*—taught alongside its empirical equivalents, so that students understand what the data actually constrain and what remains a matter of theoretical choice.

The integration of a dedicated module on alternative computational ontologies into graduate programs—even a focused course spanning a single academic term—would be a concrete, measurable step. Departments could begin with as little as a two-month module embedded in an existing computational physics course, in which students solve three to five canonical problems (perihelion precession, light deflection, time dilation, molecular bond angles) using two or more ontologically distinct frameworks. The learning outcome is not mastery of the alternatives, but the recognition that the relationship between empirical prediction and physical ontology is far less straightforward than standard textbooks suggest.

Science advances not by protecting its orthodoxies, but by stress-testing them. If we wish the next generation of physicists to make genuine conceptual breakthroughs—rather than adding ever more elaborate auxiliary constructions to existing frameworks—we must first give them the intellectual tools to imagine that the world might work differently than their textbooks suggest.

That is not a threat to physics. It is the highest standard of physics education.

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Conflict of Interest Disclosure: The author has developed one of the computational frameworks (Euclidean Field Relativity) mentioned in this paper as an example of an alternative gravitational ontology. This framework is referenced solely in its capacity as a pedagogical tool. The argument of the paper does not depend on the validity of any particular alternative theory.