philosophies

MDPI

Article

Predictive Epistemology: Complexity, Evolutionary Epistemology, and the Anticipation of Scientific Change

Miguel Fuentes [1,2]

[1] Santa Fe Institute, Hyde Park Road 1399, Santa Fe, NM 87501, USA; fuentesm@santafe.edu
[2] Instituto de Investigaciones Filosóficas-SADAF, Buenos Aires C1176ABL, Argentina

Abstract

Predictive Epistemology is developed here as a philosophical framework for identifying structural signs that an established scientific framework is becoming increasingly difficult to sustain before major theoretical reorganization occurs. Building on Effective Complexity and its constrained formalization, the framework asks how the minimum theoretical complexity required to preserve a specified level of explanatory or empirical adequacy changes as empirical demands accumulate. Theoretical stress is defined as a sustained baseline-relative increase in this constrained explanatory cost. Epistemic fragility is treated separately as reduced robustness of a framework's capacity to preserve adequacy under further relevant demands; a tipping-region diagnosis therefore requires theoretical stress together with independent evidence of declining robustness. The framework does not seek to predict the content or exact timing of successor theories. It is situated as a complement to evolutionary epistemology and examined through evolutionary biology as a reflexive test case. Three possibilities are distinguished: productive extension, stable pluralism, and theoretical stress. A minimal qualitative illustration based on niche construction shows why increased theoretical content does not by itself constitute stress, while a worked longitudinal reconstruction of the old quantum theory illustrates how the diagnostic procedure can distinguish productive extension from a later period of increasing accommodation cost. Predictive Epistemology thus offers a prospective, context-dependent, and in-principle testable framework for investigating the changing stability of scientific theories.

Keywords: predictive epistemology; theoretical stress; epistemic tipping regions; scientific theory change; evolutionary epistemology; philosophy of biology

1. Introduction: From Evolutionary to Predictive Epistemology

Evolutionary epistemology begins from a simple but consequential idea: knowledge is not static. Scientific theories, concepts, epistemic norms, and broader bodies of human knowledge change over time, and some versions of evolutionary epistemology seek to understand these changes by drawing on models and metaphors derived from evolutionary biology. This program is commonly distinguished from a second, related project concerned with the biological evolution of the cognitive mechanisms that make knowing possible. The distinction is often expressed as that between the Evolution of Epistemological Mechanisms (EEM) and the Evolutionary Epistemology of Theories (EET). Whereas EEM addresses the evolutionary origins and development of cognitive structures, EET concerns the development of ideas, theories, epistemic norms, and systems of knowledge themselves [1]. The present article is situated primarily within this second tradition.

Check for updates

Academic Editor: Srdjan Kesić

Received: 28 August 2026
Revised: 22 October 2026
Accepted: 26 October 2026
Published: 1 November 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

This evolutionary perspective naturally directs attention toward processes of theoretical variation, persistence, competition, and transformation. Yet it also raises a less explored prospective question. If scientific theories evolve, can we identify when an established theoretical framework is approaching conditions associated with substantial theoretical reorganization? Put differently, can epistemology do more than reconstruct theoretical transitions after they have occurred? Can it identify structural features of a theory's development that indicate a growing loss of explanatory stability before a major reorganization takes place?

The central research question can therefore be stated as follows:

> *Under what conditions can the baseline-relative trajectory of the minimum theoretical complexity required to preserve a specified level of adequacy, together with independent evidence of declining robustness, function as a prospective indicator of increasing epistemic fragility in an established scientific framework?*

This question motivates the proposal developed here under the name Predictive Epistemology. Predictive Epistemology seeks to identify forward-looking structural indicators that an existing scientific framework is becoming increasingly difficult to sustain under changing empirical demands. The proposal is inspired by a general insight from complexity science: in some complex dynamical systems, large-scale transitions may be preceded by changes in measurable properties of the system, making it possible to investigate early-warning signals of an approaching critical transition even when the precise future state cannot be predicted [2]. The analogy must be used carefully. Scientific theories are not physical or ecological dynamical systems in any straightforward sense, and theoretical change cannot be reduced to a bifurcation model. Nevertheless, the distinction between anticipating instability and predicting a successor state provides a useful conceptual starting point for epistemology:

$$\text{anticipating theoretical instability} \neq \text{predicting the successor theory}$$

Accordingly, Predictive Epistemology does not aim to predict the content of the theory that will replace an existing framework. Its claim is more limited. A theoretical framework may display increasing theoretical stress as it is required to accommodate new observations, domains, or explanatory demands. If maintaining comparable explanatory performance requires progressively greater theoretical complexity, through additional assumptions, parameters, special mechanisms, exceptions, or other forms of conceptual scaffolding, this trajectory may provide information about the stability of the framework itself. The former kind of anticipation may therefore be possible even when the identity and content of a successor theory remain radically underdetermined.

The initial formulation of this idea was introduced in [3]. There, changes in the information required to preserve theoretical coherence in the face of new data and anomalies were proposed as potential indicators of theoretical stress, and the notion of an epistemic tipping point was introduced to describe situations in which a framework may require substantial extension, redefinition, or replacement. The argument was developed in the broader context of emergence, effective complexity, and historical cases of theory change. The present article extends that earlier formulation in four specific respects. First, it recasts theoretical complexity as a constrained problem: the relevant quantity is the minimum structural complexity required by an admissible realization of a framework to preserve a specified level of explanatory or empirical adequacy, represented schematically as $C_T(p \mid A \geq A_0)$. Here, T denotes a theoretical framework, p indexes changing empirical demands, and A_0 represents a specified adequacy threshold. The quantity is formally defined in Section 3. This formulation draws on the logic of constrained Effective Complexity while shifting attention from static explanatory complexity to its trajectory under changing empirical demands.

Second, it generalizes the idealized notion of an epistemic tipping point into an epistemic tipping region, better suited to the multidimensional and historically distributed character of scientific change. Third, it situates Predictive Epistemology explicitly as a complement to the Evolutionary Epistemology of Theories, shifting attention from the selection and persistence of epistemic variants to the prospective diagnosis of fragility within an established framework. Fourth, it applies this diagnostic logic to evolutionary biology through the distinction between productive extension, stable pluralism, and theoretical stress, including a minimal qualitative application to niche construction. Together, these developments transform the earlier proposal from a concluding implication of a broader analysis of complexity and emergence into the explicit philosophical framework examined here.

Evolutionary biology is appropriate for this purpose not merely because it supplies the conceptual source of evolutionary epistemology, but because evolutionary theory has itself undergone substantial historical development, integration, extension, and internal debate. It therefore provides a reflexive case in which a scientific framework concerned with explaining evolutionary change can itself be examined as an evolving epistemic system. The question is not whether present evolutionary theory is necessarily approaching a crisis, nor whether any particular extension will replace an established synthesis. It is whether a complexity-based epistemology, rooted in information theory, can distinguish productive theoretical extension from trajectories in which preserving explanatory adequacy demands increasingly costly theoretical accommodation.

The structure of the article follows this argument. Section 2 identifies the prospective problem that motivates Predictive Epistemology and clarifies its complementary relation to evolutionary epistemology. Section 3 develops the diagnostic framework in terms of constrained theoretical complexity, theoretical stress, epistemic fragility, and epistemic tipping regions. Section 4 applies these distinctions to evolutionary biology, distinguishing productive extension, stable pluralism, and theoretical stress. Section 5 provides a worked longitudinal reconstruction of the old quantum theory in order to show how the diagnostic can be applied across an evolving theoretical trajectory. Section 6 specifies the scope and limits of what Predictive Epistemology can legitimately claim, and Section 7 summarizes the resulting framework and its prospective character.

2. Evolutionary Epistemology and the Problem of Anticipation

Evolutionary epistemology provides a natural starting point for thinking about scientific knowledge as a process rather than as a fixed body of propositions. As noted above, however, the term encompasses two related but distinct programs. The Evolution of Epistemological Mechanisms (EEM) concerns the biological evolution of the cognitive capacities that make knowledge possible, whereas the Evolutionary Epistemology of Theories (EET) applies evolutionary models and analogies to the development of ideas, scientific theories, epistemic norms, and systems of knowledge [1]. The present argument belongs primarily to EET. Its purpose is not to replace an evolutionary account of scientific change, but to identify a question that becomes visible once knowledge is taken seriously as an evolving system: whether the approach toward major theoretical reorganization can itself exhibit identifiable structural precursors.

2.1. Evolutionary Epistemology of Theories

The central intuition behind the Evolutionary Epistemology of Theories (EET) is that scientific knowledge can be understood, at least in part, as an evolving process involving the generation, differential evaluation, persistence, and transformation of epistemic variants. Campbell's account of blind variation and selective retention provided one influential formulation of this idea [4,5], while Popper interpreted the growth of scientific knowledge in

terms of conjecture, criticism, and error elimination [6]. Toulmin extended the evolutionary perspective to historically changing conceptual populations and disciplinary standards [7], and Hull emphasized the social organization, transmission, and differential success of scientific lineages [8].

Despite their substantial differences, these approaches share enough structure to motivate the heuristic representation

$$\text{Variation} \rightarrow \text{Selection} \rightarrow \text{Retention}.$$

This sequence should not be interpreted as attributing a common mechanism to these authors, whose units of analysis and philosophical commitments differ substantially [9]. It identifies only a broad orientation toward explaining how epistemic variants arise, persist, and are transformed.

Predictive Epistemology is not formally derived from this evolutionary framework, and its constrained-complexity diagnostic does not depend on variation–selection–retention assumptions. The relationship is complementary rather than derivational. EET provides conceptual resources for understanding the generation, persistence, selection, and transformation of epistemic variants. Predictive Epistemology asks a different but related prospective question: whether the established theoretical regime within which such variation occurs exhibits identifiable changes in structural cost and robustness before substantial reorganization.

2.2. The Prospective Question

This distinction can be expressed through two different questions. An evolutionary epistemology may ask:

Why did this theoretical variant survive, spread, or replace competing alternatives?

Predictive Epistemology adds a different question:

Was the preceding theoretical regime already displaying identifiable structural signs of increasing theoretical stress?

The first question concerns the dynamics of epistemic variants and their differential persistence. The second concerns the state of the established framework before substantial reorganization occurs. It therefore shifts attention from the fate of alternatives to the evolving stability of the theoretical regime within which those alternatives become relevant.

The distinction is analogous, although not reducible, to an important distinction in complexity science. In many nonlinear systems, explaining the dynamics that produce alternative states is different from investigating whether the system's present state exhibits indications of declining stability as relevant conditions change. Research on critical transitions has shown that, in some physical, ecological, and other complex systems, transitions may be preceded by changes in system-level properties, allowing the search for early-warning indicators even when the identity or detailed structure of the subsequent state remains uncertain [2]. As emphasized in the Introduction, scientific theories should not therefore be treated literally as ecological or physical systems. The relevance of complexity science at this stage is conceptual: it provides a vocabulary for distinguishing stability from change, gradual adaptation from nonlinear response, stable regions from critical regions, and increasing complexity from relatively economical accommodation.

This prospective orientation also changes what counts as philosophically interesting evidence. An anomaly by itself does not demonstrate that a theory is unstable, just as the addition of an auxiliary assumption does not by itself indicate degeneration. Mature theories routinely absorb new phenomena by becoming richer and more differentiated. The relevant question is therefore not whether theoretical complexity increases, but whether there are systematic changes in the amount and character of the complexity required to preserve

explanatory adequacy as empirical demands expand. If such changes can be characterized, they may provide information not about what theory will come next, but about the changing stability of the theory currently in place.

The proposal developed in the following section begins from this possibility. Section 3 turns the prospective problem identified here into an explicit diagnostic framework by specifying constrained theoretical complexity, theoretical stress, and epistemic fragility. Its relation to evolutionary epistemology remains complementary: evolutionary epistemology concerns the dynamics of epistemic change, whereas Predictive Epistemology isolates a prospective diagnostic problem concerning the stability of an established theoretical regime.

3. Predictive Epistemology: Complexity, Theoretical Stress, and Epistemic Tipping Regions

The prospective question identified in the preceding section requires a way of characterizing not only whether a scientific framework succeeds, but how the theoretical resources required for that success change as empirical demands evolve. A framework may accommodate new observations through relatively economical extensions of its existing structure, or it may require increasingly elaborate modifications to preserve a comparable level of performance. Predictive Epistemology begins from the hypothesis that the trajectory of this theoretical cost can itself contain epistemically relevant information. The central object of analysis is therefore not complexity in isolation, but the changing complexity required to maintain explanatory or empirical adequacy.

The proposal draws on Effective Complexity and its subsequent formal development, but it does not identify scientific theories literally with algorithmic objects or probability distributions. Rather, these formalisms provide a technical model of an epistemologically important distinction: an explanation may become more structurally elaborate while continuing to accommodate the phenomena it is required to explain. Predictive Epistemology asks whether the evolution of that explanatory cost can be studied prospectively.

The formal notation introduced below is intended to make the structure of the proposal explicit rather than to make the philosophical argument depend on technical calculation; readers can follow the central argument through the accompanying conceptual interpretation.

3.1. From Effective Complexity to Parametric Theoretical Complexity

The conceptual starting point is Effective Complexity, introduced by Gell-Mann and Lloyd [10,11] to distinguish the information contained in the regularities of an entity from information treated as random or incidental. This distinction addresses a familiar limitation of algorithmic information content: a random string may have very high Kolmogorov complexity even though it contains little organized structure. Effective Complexity instead concerns the description length of those regularities judged relevant at a specified level of description.

This qualification is essential. Gell-Mann and Lloyd emphasize that Effective Complexity is context-dependent: it depends on the coarse graining adopted, the descriptive language, relevant background knowledge, and, crucially, the distinction made between regular and incidental features [11]. What counts as complexity is therefore not specified independently of an explanatory context. This feature is particularly appropriate for an epistemological application, where different scientific problems may legitimately privilege different regularities, variables, mechanisms, and levels of description.

A useful way of making the underlying trade-off explicit is to represent an explanatory ensemble by E. Let $K(E)$ denote the Kolmogorov complexity of the ensemble, and $H(E)$ its

Shannon entropy. Following Gell-Mann and Lloyd [11], the corresponding total information is given by

$$\Sigma(E) = K(E) + H(E). \tag{1}$$

This decomposition has a direct epistemological interpretation. A satisfactory explanation should, other things being equal, remain structurally economical, so that $K(E)$ is not unnecessarily large, while also restricting the space of admissible outcomes sufficiently to account for the data, so that $H(E)$ is not excessively large. These desiderata may conflict. A theory may concentrate more narrowly on the observed data by adding parameters, auxiliary mechanisms, or special provisions, but only at the cost of increasing the complexity of the theoretical description. Conversely, a simpler theory may remain compatible with the data only by allowing a much wider range of possible outcomes [11].

This static trade-off already captures an important intuition behind the present proposal. However, Predictive Epistemology adds a different question. It is not concerned primarily with locating a single optimal explanatory representation at one moment, but with asking how the structural cost of maintaining an acceptable explanation changes as the empirical demands imposed on a framework evolve.

The subsequent formalization of Effective Complexity by Ay, Müller, and Szkoła makes this idea more precise [12]. Given data represented by a string x, an admissible explanatory ensemble E must not only possess sufficiently low total information; x must also be typical for that ensemble. In their formulation, x is δ-typical for E when

$$E(x) \geq 2^{-H(E)(1+\delta)}. \tag{2}$$

Effective Complexity can then be defined through a minimization over ensembles that render the observed data sufficiently typical while keeping total information within a specified tolerance:

$$\mathcal{E}_{\delta,\Delta}(x) = \min_{E}\{K(E) : x \text{ is } \delta\text{-typical for } E,\ \Sigma(E) \leq K(x) + \Delta\}. \tag{3}$$

Ay et al. also develop a constrained version,

$$\mathcal{E}_{\delta,\Delta}(x \mid C) = \min_{E \in C}\{K(E) : x \text{ is } \delta\text{-typical for } E,\ \Sigma(E) \leq K(x) + \Delta\}, \tag{4}$$

where C denotes the restricted class of admissible ensembles induced by additional conditions that an explanation must satisfy. Such conditions may encode observables or properties regarded as explanatorily important. Their role is philosophically significant: the complexity of an adequate explanation depends not only on the data themselves, but also on which regularities the explanatory problem requires the theory to preserve. This restriction is not merely technical. Without appropriate constraints, minimization can favor representations that are formally economical while failing to preserve the regularities regarded as explanatorily relevant. The specification of admissibility conditions is therefore part of the epistemic problem itself.

Predictive Epistemology does not simply identify a scientific theory T with an ensemble E, nor does it require that scientific adequacy be reducible to algorithmic typicality. The relevance of this formalism is structural. It shows that explanatory complexity can be defined relative to admissibility conditions and that the appropriate object of comparison is not unconstrained descriptive complexity, but the minimum structural complexity required to satisfy specified explanatory demands.

Building on this idea, previous work introduced a parametric form of Effective Complexity, or P-Effective Complexity, in which complexity is examined as a function of a relevant control parameter [3,13]. Let C_p denote the Effective Complexity associated with a particular value of a parameter p. If the relevant regularities of a system change as p changes,

the complexity required to represent those regularities may also change. In the original formulation, discontinuous changes in parametric complexity were used to characterize the emergence of new properties and to connect changes in system behavior with changes in the informational requirements of their theoretical description [13].

Predictive Epistemology generalizes this parametric idea from the represented complexity of a system to the complexity required by an established scientific framework to continue accounting for a changing empirical domain. Let T denote a scientific theoretical framework, and let p represent an epistemically relevant ordering of changes in the conditions under which the framework is required to operate. We may then write $C_T(p)$ for the theoretical complexity required for T to provide an adequate account of the relevant phenomena at a given position along p.

The parameter p need not be a physical control parameter such as temperature, pressure, or concentration. In epistemological applications, it may represent an ordered sequence of empirical domains, increasing observational precision, an expansion across spatial or temporal scales, the incorporation of additional classes of phenomena, or another dimension along which the demands placed upon a theory can be meaningfully compared. The requirement is weaker than a physical parametrization: changes along p must simply admit a sufficiently well-defined ordering for comparisons of explanatory cost to be meaningful.

The quantity $C_T(p)$ should likewise be understood initially as a conceptual function rather than as a commitment to one universal numerical measure of theoretical complexity. Depending on the scientific domain, relevant proxies may include independently adjusted parameters, auxiliary assumptions, distinct mechanisms, exceptional clauses, restrictions on domain, computational resources, descriptive length, or combinations of these. Statistical model selection and description-length approaches provide familiar examples in which empirical performance is evaluated together with model complexity [14–16]. The algorithmic formulation therefore supplies a conceptual foundation rather than requiring that exact Kolmogorov complexity be calculated in every empirical application. The relation between these approaches and the longitudinal criterion proposed here is clarified below.

The crucial shift introduced here is from a static optimization problem to a trajectory:

$$\text{constrained explanatory complexity} \quad \longrightarrow \quad \text{trajectory of constrained explanatory complexity.} \tag{5}$$

It is this trajectory, rather than complexity at a single point, that becomes epistemically diagnostic.

3.2. Fixing Explanatory Adequacy

A straightforward objection immediately arises. Scientific theories often become more complex because they explain more phenomena, operate at higher precision, or integrate previously separate domains. Increasing theoretical complexity is therefore not, by itself, evidence of epistemic difficulty. A framework that successfully explains substantially more may legitimately require additional parameters, mechanisms, auxiliary assumptions, or conceptual distinctions. Any attempt to use complexity diagnostically must therefore distinguish the growth of theoretical complexity from the growth of explanatory achievement.

Predictive Epistemology addresses this problem by evaluating theoretical complexity under an explicit adequacy constraint. Let T denote the scientific theoretical framework under investigation, as introduced above, and let $\mathcal{R}(T)$ denote the class of admissible models, formulations, or theoretical realizations associated with that framework for the purposes of a specified analysis. For a particular realization $\tau \in \mathcal{R}(T)$, let $A(\tau, p)$ denote its empirical or explanatory adequacy under the conditions indexed by p, and let A_0 denote a domain-appropriate adequacy threshold. Finally, let $\kappa(\tau)$ denote the domain-specific measure or proxy used to represent the theoretical complexity of that realization.

The relevant object is then not the complexity of an arbitrary realization of T, but the lowest theoretical complexity compatible with the specified adequacy requirement. Schematically,

$$C_T(p \mid A \geq A_0) = \inf_{\substack{\tau \in \mathcal{R}(T) \\ A(\tau,p) \geq A_0}} \kappa(\tau). \tag{6}$$

The use of the infimum rather than a minimum is deliberate. The formulation does not assume that, for every scientific framework and every value of p, there exists a uniquely identifiable realization that exactly attains the lowest possible complexity. It requires only that admissible realizations can, in principle, be compared with respect to the complexity needed to satisfy the adequacy condition. The vertical bar in $C_T(p \mid A \geq A_0)$ denotes restriction to realizations satisfying this adequacy requirement; it should not be interpreted as algorithmic conditional complexity.

The expression is intended for regions in which at least one admissible realization of T continues to satisfy the adequacy threshold. If no $\tau \in \mathcal{R}(T)$ satisfies $A(\tau, p) \geq A_0$, the issue is no longer the increasing theoretical cost of maintaining adequacy but an explicit loss of adequacy. This case is conceptually distinct from theoretical stress as defined here, which concerns situations in which a framework continues to meet the relevant standard while doing so at an increasing structural cost.

The central question can therefore be stated more precisely:

> How does the minimum theoretical complexity required by an admissible realization of framework T to preserve a comparable level of adequacy change as the empirical demands represented by p evolve?

This formulation is structurally related to the constrained version of Effective Complexity discussed above, but the two should not be identified [12]. The parameters δ and Δ, the class of admissible ensembles, and algorithmic typicality belong to a specific formal theory of Effective Complexity. In Predictive Epistemology, by contrast, $\mathcal{R}(T)$, $A(\tau, p)$, A_0, and $\kappa(\tau)$ are domain-dependent epistemological constructs. The relevance of the algorithmic formalism is that it provides a rigorous precedent for asking about the least complex representation satisfying specified admissibility conditions.

The value of A_0 need not be universal. In a quantitatively mature field it may correspond to predictive accuracy, goodness of fit, error tolerance, or another explicitly specified performance criterion. In less easily quantified contexts it may refer to explanatory coverage, consistency with established observations, successful accommodation of specified phenomena, or another discipline-specific standard. What is required is not a single cross-disciplinary measure of scientific success, but a sufficiently explicit and stable criterion to permit comparison within the trajectory under investigation.

Fixing A_0 does not require the empirical domain itself to remain fixed. The phenomena, observables, scales, or explanatory requirements over which adequacy is evaluated may expand or change along p. What must remain sufficiently stable is the rule by which adequacy is assessed, so that values of $A(\tau, p)$ remain meaningfully comparable across different positions along the trajectory. Thus, A_0 represents a common performance threshold applied under changing empirical demands, rather than a requirement that the empirical content being explained remain identical. Where changes in the empirical domain also require changes in the adequacy measure itself, those changes must be explicitly specified or calibrated; otherwise, comparisons of $C_T(p \mid A \geq A_0)$ across p would lose their diagnostic meaning.

This conditional formulation makes the philosophical claim comparative rather than absolutist. Predictive Epistemology does not assume that simpler theories are always epistemically superior, nor does it identify complexity itself with theoretical weakness.

Simplicity is relevant only in relation to what a theoretical realization accomplishes [14,15]. A structurally richer realization that achieves substantially greater explanatory coverage may represent genuine theoretical progress. The potential warning sign arises instead when preserving comparable adequacy requires disproportionately increasing theoretical resources.

The formulation is deliberately schematic: neither the boundary of $\mathcal{R}(T)$ nor the appropriate complexity proxy is assumed to be unique across scientific domains. This contextuality, however, does not license unrestricted specification. A prospective application should satisfy three requirements. First, *outcome independence*: T, $\mathcal{R}(T)$, p, A_0, κ, and the comparative baseline should be specified without using the subsequent theoretical outcome as a criterion for their selection. Second, *domain anchoring*: each choice should be justified by independently defensible features of the scientific practice under study, such as recognized model classes, empirical targets, performance standards, or theoretical commitments. Third, *specification robustness*: where several reasonable specifications remain available, a diagnosis of theoretical stress should not depend solely on one particular choice, but should remain supported across a reasonable range of admissible alternatives. These requirements do not eliminate context-dependent judgment; they constrain the retrospective flexibility with which the framework can be applied.

Predictive Epistemology is therefore fundamentally trajectory-based. The relevant question is not whether framework T is complex at a particular moment, but how $C_T(p \mid A \geq A_0)$ changes as the empirical demands placed upon the framework develop.

3.3. Theoretical Stress

The trajectory of the minimum complexity compatible with the adequacy constraint allows a more precise definition of theoretical stress:

> *Theoretical stress occurs when maintaining a specified level of explanatory or empirical adequacy requires a disproportionate increase in the minimum theoretical complexity of admissible realizations of an established framework.*

The word *disproportionate* is essential. It prevents every increase in theoretical complexity from being interpreted as evidence of stress. Let $B_T(p)$ denote the comparative baseline trajectory fixed for a particular application. A disproportionate increase is understood here as a sustained departure of $C_T(p \mid A \geq A_0)$ from that baseline in the direction of greater accommodation cost, beyond the variation treated as ordinary for the comparison under consideration. A single departure is therefore insufficient. What matters is a persistent change in the cost required to preserve the specified level of adequacy.

Where the relevant quantities admit a numerical representation, this departure may be expressed schematically as the excess complexity $D_T(p)$ relative to the baseline:

$$D_T(p) = C_T(p \mid A \geq A_0) - B_T(p). \tag{7}$$

Theoretical stress does not follow merely from $D_T(p) > 0$. The diagnostic requirement is that the departure be sustained over an epistemically meaningful portion of the trajectory. Where complexity is represented only ordinally or qualitatively, the same principle applies comparatively without requiring numerical subtraction.

This criterion does not require a universally nonlinear trajectory. In a particular scientific domain, a change in slope, declining marginal explanatory return, or another quantitative feature may provide an appropriate operationalization. The general requirement is weaker: continued adequacy must be associated with a sustained excess of accommodation cost relative to the independently specified baseline.

This idea has an important antecedent in Gell-Mann and Lloyd's account of total information. They explicitly note that a scientific theory may be made to fit or concentrate more tightly on the observed data by introducing additional parameters and theoretical "bells and whistles," but only at the expense of increasing the complexity of the theory [11]. Their formulation captures a static trade-off between explanatory concentration and structural complexity. Predictive Epistemology retains this intuition but adds a longitudinal question: whether that cost departs systematically from the regime against which theoretical development is being compared.

In practice, such accommodation may involve additional auxiliary hypotheses, independently adjusted parameters, distinct mechanisms, special-case treatments, explicit exceptions, restrictions on domain of applicability, or increasingly elaborate computational and conceptual scaffolding. None of these features is intrinsically problematic. What matters is their cumulative role in maintaining the specified level of adequacy relative to the chosen baseline.

Consider a framework that repeatedly encounters new empirical demands. At an early stage, these demands may be incorporated through modest extensions that preserve the economy of the framework. Later, comparable increments in empirical or explanatory coverage may require several independent assumptions, additional mechanisms, or increasingly restricted clauses. The framework may remain empirically successful throughout this process. Yet if preserving comparable adequacy systematically requires greater structural expenditure, its success is being achieved at an increasing theoretical cost.

It is this combination,

$$\text{continued adequacy} + \text{sustained excess accommodation cost}, \tag{8}$$

rather than complexity growth alone, that constitutes theoretical stress.

This formulation distinguishes theoretical stress from simple empirical falsification. A framework need not contradict the observations. Indeed, the philosophically interesting situation is precisely one in which a theory continues to work while requiring progressively more structure in order to do so. Predictive Epistemology is therefore concerned with conditions that may precede explicit failure. In this respect, it develops the possibility suggested in the earlier formulation of parametric complexity: increasing informational requirements may reveal epistemic difficulties before they appear as straightforward empirical contradiction [3].

The same distinction separates the proposal from a crude appeal to simplicity. The question is not whether one theory contains fewer symbols, assumptions, or parameters than another at a single moment. It is whether the structural cost of maintaining adequacy departs persistently from the independently specified baseline along an epistemically meaningful trajectory. This dynamic element gives theoretical stress its prospective significance.

The distinction also helps locate theoretical stress relative to neighboring accounts of scientific development. Lakatos's distinction between progressive and degenerating problem shifts is especially close to the present proposal [17]. For Lakatos, a research programme is progressive when its successive theoretical changes are accompanied by novel empirical content, whereas a degenerating shift primarily accommodates already known difficulties. Predictive Epistemology evaluates a different dimension: the changing structural cost required to preserve a specified level of adequacy. The two criteria can therefore diverge. A programme may remain progressive in Lakatos's sense while requiring increasingly costly theoretical accommodation; conversely, a simple post hoc modification may be degenerating without producing a substantial change in the minimum adequate complexity considered here. Theoretical stress is therefore not a quantitative definition of Lakatosian degeneration or of ad hocness.

A related distinction applies to statistical model selection and description-length approaches. Criteria that balance fit against complexity, including Akaike-style model selection and minimum-description-length methods, provide principled ways of comparing alternative models or representations for a given inferential problem [14–16]. Predictive Epistemology does not propose a new general model-selection criterion. Its object is longitudinal: it asks how the minimum structural cost compatible with a specified level of adequacy changes within an established theoretical framework as empirical demands evolve. Model-selection criteria therefore concern which representation is preferable under specified data and objectives, whereas theoretical stress concerns whether the cost of remaining adequate is itself changing systematically over the development of a framework.

Nor does Predictive Epistemology treat explanatory unification as an unconditional epistemic virtue: as the possibility of stable pluralism makes clear, the relevant diagnostic question is not whether a framework remains fully unified, but whether preserving the specified level of adequacy requires a sustained excess of structural accommodation relative to its baseline.

3.4. Epistemic Tipping Regions

The concept of theoretical stress makes it possible to introduce a second central notion: the *epistemic tipping region*.

Theoretical stress and epistemic fragility should not be identified. Theoretical stress concerns the baseline-relative structural cost required to preserve a specified level of adequacy. Epistemic fragility concerns a different property: the reduced robustness of a theoretical framework's capacity to preserve that adequacy under further relevant empirical or explanatory demands. A framework may therefore exhibit theoretical stress while remaining robust if the additional structure is reusable, well integrated, or supports further extension. Conversely, a comparatively simple framework may become fragile if a central theoretical commitment is undermined.

Accordingly, theoretical stress is neither a necessary nor a sufficient condition for epistemic fragility. It is treated here as a defeasible indicator. Its diagnostic significance is strengthened when sustained excess accommodation cost is accompanied by independent evidence of declining robustness, such as increasing sensitivity to further demands, contraction of the set of realizations capable of meeting the adequacy requirement, or growing dependence on narrowly specialized auxiliary structures. These features are illustrative rather than universal and must be specified within the scientific domain under investigation.

The terminology is deliberately inspired by research on critical transitions in complex systems. In ecological and other nonlinear systems, changes in system-level properties may sometimes indicate declining resilience as a transition is approached [2,18]. Research on early-warning indicators has likewise emphasized that such signals are probabilistic, context-sensitive, and neither necessary nor sufficient predictors of a particular subsequent state [19]. These qualifications are especially important when the analogy is transferred to epistemology.

There is also a more specific formal precedent within the literature on Effective Complexity. Ay, Müller, and Szkoła establish, under explicit technical conditions, a threshold-like relation between Effective Complexity and Bennett's logical depth [12,20]: above a certain complexity threshold, the logical depth of a string must become extremely large, whereas below that threshold shallow behavior remains possible. They describe this change as reminiscent of a phase transition.

This result should not be interpreted as a mathematical demonstration of epistemic tipping in scientific theories. Logical depth concerns the computational resources required to generate algorithmic objects, whereas Predictive Epistemology concerns the structural

cost of maintaining explanatory adequacy in scientific frameworks. The relevance is more limited but still significant: formal work on Effective Complexity shows that threshold-like changes in related informational quantities are possible and need not be introduced purely metaphorically. It therefore provides a precedent for investigating whether qualitative changes in epistemic stability may emerge along trajectories of constrained complexity.

An epistemic tipping region is defined here as:

> *A domain in which sustained theoretical stress, together with independent evidence of declining robustness, supports a defeasible diagnosis of increasing epistemic fragility.*

Let $\mathcal{D}^*$ denote a region of the empirical-demand space in which the constrained complexity trajectory exhibits sustained baseline-relative stress and the framework simultaneously displays relevant signs of declining robustness. The complexity component of this diagnosis can be represented schematically as follows.

Schematically, one may contrast a regime in which

$$p \notin \mathcal{D}^* : \qquad C_T(p \mid A \geq A_0) \text{ follows its baseline regime,} \tag{9}$$

with a regime in which relevant conditions approach the tipping region,

$$p \to \mathcal{D}^* : \qquad D_T(p) \text{ exhibits a sustained positive departure.} \tag{10}$$

These expressions represent only the complexity-trajectory component of the diagnosis; evidence of declining robustness remains conceptually independent of C_T. The notation $\mathcal{D}^*$ is deliberately regional rather than point-like. Scientific change rarely provides the sharply specified control parameters, state spaces, and bifurcation thresholds available in idealized dynamical systems. Empirical demands may change simultaneously along several dimensions; historical evidence may be incomplete; and theoretical modifications themselves can alter which subsequent problems and observations become salient.

Predictive Epistemology therefore does not require a uniquely defined critical point at which theoretical revolution becomes inevitable. It seeks domains in which sustained theoretical stress and independently specified signs of declining robustness jointly support a diagnosis of increasing epistemic fragility.

Most importantly, entering such a region does not logically imply the replacement of T by a successor framework T'. An established framework may recover through conceptual innovation, absorb previously problematic phenomena, reorganize internally, fragment productively into specialized models, or coexist with alternative frameworks. Predictive Epistemology therefore advances a comparative empirical hypothesis rather than a calibrated probabilistic claim: independently specified episodes of sustained theoretical stress, when accompanied by evidence of declining robustness, should be associated more frequently with subsequent substantial theoretical reorganization than comparable periods of stable theoretical development.

This hypothesis does not imply that reorganization must follow in any individual case. It identifies a relation that can be assessed comparatively across theoretical histories.

In this respect, the concept preserves the central insight of early-warning approaches in complexity science, the possibility of diagnosing declining stability without specifying the subsequent state, while avoiding the stronger and unjustified claim that scientific theories literally undergo physical bifurcations.

The concept also generalizes the earlier formulation of an epistemic tipping point [3]. The term *point* may remain useful in idealized or retrospectively reconstructed cases where a relatively sharp critical value can be meaningfully identified. For the general philosophical framework developed here, however, *tipping region* better represents the uncertainty, multidimensionality, and historically distributed character of theoretical transformation.

3.5. Definition of Predictive Epistemology

The preceding concepts allow the central proposal of this article to be stated more precisely.

> *Predictive Epistemology is the study of structural and informational indicators through which increasing theoretical stress and the approaching loss of explanatory stability of a scientific framework may be identified before major theoretical reorganization occurs.*

Its prospective object is therefore increasing epistemic fragility, not the content of future knowledge.

This distinction separates three claims that should not be conflated.

First, one might attempt to predict the *content* of a future theory: what concepts, entities, mechanisms, or laws it will contain. Predictive Epistemology makes no such claim.

Second, one might attempt to predict the exact *timing* of theoretical replacement. The present framework does not require this either.

Third, one may ask whether an established framework exhibits a changing structural trajectory that can be tested as a prospective indicator of subsequent substantial reorganization. It is this third and more limited form of anticipation that defines the present program.

The distinction can be summarized as

$$\text{diagnosing increasing epistemic fragility} \neq \text{predicting future theoretical content.} \quad (11)$$

Predictive Epistemology is therefore neither a theory of scientific prophecy nor a claim that the future development of knowledge can be deterministically derived from present conditions. Its ambition is more limited but potentially testable: to determine whether changes in the minimum theoretical complexity required to preserve comparable explanatory adequacy can function as forward-looking indicators of declining explanatory stability.

The conceptual progression can be outlined as

$$\begin{aligned}\text{Effective Complexity} &\longrightarrow \text{minimum adequate complexity} \longrightarrow \text{baseline-relative trajectory} \\ &\longrightarrow \text{theoretical stress}\end{aligned}$$

Theoretical stress may then contribute to a diagnosis of epistemic fragility when it is accompanied by independent evidence that the framework's robustness under further relevant demands is declining.

Gell-Mann and Lloyd provide a framework for distinguishing the structured information of an explanation from its residual uncertainty and for understanding the trade-off between explanatory concentration and theoretical complexity. Ay et al. show how this intuition can be formalized through typicality, total-information bounds, and constrained minimization. Predictive Epistemology adds the prospective step: it asks whether the baseline-relative trajectory of the minimum structural cost required to maintain adequacy can function as one defeasible indicator of increasing epistemic fragility when assessed together with independent evidence that robustness is declining.

This formulation transforms the proposal from a retrospective observation about historical episodes into a research framework. It identifies an object, the evolving complexity of an established theory; a comparative constraint, the preservation of a specified level of adequacy; a diagnostic condition, the accumulation of theoretical stress; and a prospective target, the approach to a region of increased epistemic fragility.

The next question is whether these distinctions illuminate an actual domain of scientific development. Evolutionary biology provides a particularly revealing case because the theory that explains biological evolution has itself undergone continuing extension, integration, diversification, and conceptual reorganization.

4. Evolutionary Biology as a Reflexive Test Case

Evolutionary biology provides an unusually revealing domain in which to examine the framework developed above. It is not simply one scientific field among others to which Predictive Epistemology might eventually be applied. A scientific framework devoted to explaining evolutionary change has itself undergone, and continues to undergo, substantial theoretical evolution. Evolutionary biology therefore creates a reflexive situation in which the dynamics of a theory about biological evolution can be examined through an epistemology concerned with the evolution and stability of scientific frameworks themselves.

This reflexivity is particularly relevant to evolutionary epistemology. Evolutionary epistemology asks how ideas, theories, and epistemic practices vary, persist, and change; evolutionary biology supplies both the conceptual vocabulary from which this tradition historically drew and an actual scientific case in which theoretical structures have repeatedly been reorganized. The resulting question is not whether scientific theories evolve in exactly the same way as organisms. As emphasized above, that analogy would be too strong. Rather, evolutionary biology allows us to ask a more specific question: when a mature framework repeatedly incorporates new phenomena, mechanisms, levels, and explanatory demands, how can productive theoretical evolution be distinguished from increasing theoretical stress?

This problem is already visible in contemporary philosophy of evolutionary biology. Discussions of macroevolution, for example, raise the metascientific question of how much a theory can be modified or extended before it either becomes a substantially different theory or acquires increasingly ad hoc features [21]. The issue is therefore not artificially imposed by Predictive Epistemology. What the present framework adds is a way of reformulating the problem prospectively: instead of asking only, retrospectively, whether a theoretical transformation has occurred, we ask whether the trajectory of theoretical accommodation itself contains information about the changing stability of the framework.

4.1. Why Evolutionary Biology?

The suitability of evolutionary biology becomes clearer once one recognizes the diversity of theoretical expansions that have occurred since the twentieth-century evolutionary synthesis. Evolutionary theory has incorporated new empirical domains, new methods, new forms of data, and new explanatory questions while retaining considerable continuity with earlier theoretical commitments. The field therefore displays precisely the combination of persistence and transformation that motivates the distinction between evolutionary and predictive epistemology.

This does not mean that evolutionary biology is presently undergoing a crisis. Nor does the existence of theoretical disagreement itself constitute evidence of an epistemic tipping region. Contemporary disputes about the status and scope of the Modern Synthesis illustrate instead a more subtle problem. Some authors regard developments in evolutionary developmental biology, developmental plasticity, inclusive inheritance, and niche construction as motivating a substantially extended conceptual framework [22,23]. Others argue that evolutionary theory has always been capable of expansion and that these developments can largely be accommodated without changing its central explanatory commitments [24]. The important point for the present argument is not which side is correct. It is that the same expansion of empirical and explanatory content can be interpreted either as normal theoretical development or as evidence that the existing framework requires increasingly significant conceptual restructuring.

Predictive Epistemology is designed precisely for this kind of situation.

4.2. A Relatively Stabilized Framework

For present purposes, the Modern Synthesis can be treated as a historically stabilized theoretical reference point rather than as a single, rigidly axiomatized theory. The synthesis that emerged during the first half of the twentieth century brought Darwinian natural selection into systematic relation with Mendelian inheritance and population genetics, while integrating contributions from systematics, zoology, botany, and paleontology [25]. Population genetics supplied a mathematical account of evolutionary change in populations, while the broader synthesis connected those processes to organismal diversity and longer-term evolutionary patterns.

Schematically, its stabilizing achievement can be represented as an integration of

$$\text{natural selection} + \text{Mendelian inheritance} + \text{population genetics} + \text{additional biological domains}.$$

The important epistemological feature is not the precise historical boundary of the synthesis, which remains a matter of historiographical interpretation, but its ability to organize previously heterogeneous biological problems within a relatively coherent explanatory framework. In the terminology introduced above, the synthesis achieved a period in which a wide range of empirical demands could be accommodated without requiring continual reconstruction of the framework's basic architecture.

Calling this framework relatively stabilized is important. Evolutionary biology did not cease to change after the synthesis. As Futuyma [24] emphasizes, evolutionary theory has undergone almost continuous extension, including major developments in molecular biology, neutral evolution, quantitative genetics, genomics, and other domains. The existence of such extensions is therefore not evidence against the stability of the framework. On the contrary, the ability to assimilate new knowledge while preserving explanatory coherence is one of the marks of a successful scientific theory.

This is exactly why the distinction introduced in Section 3 matters. Predictive Epistemology is not concerned with whether $C_T(p)$ increases. Mature scientific frameworks should often become richer. The relevant issue is the trajectory of $C_T(p \mid A \geq A_0)$: how much additional theoretical structure must be introduced to preserve an appropriate level of explanatory adequacy as the domain of application expands.

4.3. Expanding Empirical and Explanatory Demands

Several developments in contemporary evolutionary biology provide useful examples of such expansion. Evolutionary developmental biology has renewed attention to the role of developmental processes in generating and constraining phenotypic variation [23]. Developmental plasticity emphasizes the ability of organisms to produce different phenotypes in response to environmental conditions and raises questions about the relation between developmental change and subsequent evolutionary processes [26]. Niche-construction theory focuses on the capacity of organisms to modify their environments and thereby alter the selective conditions experienced by themselves and their descendants [27]. Work on non-genetic inheritance has expanded discussion of heredity beyond DNA sequence alone to include epigenetic, behavioral, and other forms of intergenerational transmission [28]. Debates about multilevel selection examine evolutionary processes operating across different levels of biological organization [29], while work on self-organization has emphasized the possibility that endogenous physical and developmental dynamics contribute to biological order and evolutionary form [23,30].

These developments should not be grouped together as a collection of anomalies. They differ substantially in empirical support, theoretical role, historical origin, and relation to established evolutionary explanations. Nor does their existence imply that the Modern

Synthesis has been falsified or superseded. Indeed, one of the most illuminating features of the contemporary debate is precisely that their theoretical significance is contested.

Laland et al. [22], for example, explicitly distinguish between two possible readings of developments such as evo-devo, developmental plasticity, inclusive inheritance, and niche construction. On one interpretation, these phenomena can be incorporated while preserving the fundamental organization of contemporary evolutionary theory. On another, their explanatory importance motivates a reorganization of the conceptual framework, what those authors characterize as an Extended Evolutionary Synthesis. Futuyma [24], by contrast, argues that evolutionary theory has repeatedly incorporated new discoveries without requiring replacement of its fundamental structure and sees no compelling evidence that contemporary developments require a qualitatively new synthesis.

Predictive Epistemology need not adjudicate this dispute in advance. It changes the question.

Instead of asking simply

Does evolutionary theory need to be replaced or extended?

We ask:

Can these additional empirical and explanatory domains be incorporated through productive theoretical extension, or does maintaining an integrated framework require progressively increasing theoretical cost?

The distinction is subtle but consequential. It turns a dispute over labels, Modern Synthesis, Extended Synthesis, standard evolutionary theory, into a question about the trajectory of explanatory accommodation.

4.4. Three Epistemic Possibilities

Within the framework developed in Section 3, at least three epistemically distinct outcomes are possible.

4.4.1. Productive Extension

The first possibility is that the framework expands while retaining explanatory economy. New mechanisms, variables, or domains may increase the minimum theoretical complexity required to preserve adequacy,

$$C_T(p \mid A \geq A_0) \uparrow,$$

without producing a disproportionate departure from the relevant baseline. The increase in theoretical cost is then commensurate with the additional empirical or explanatory demands being accommodated. Developmental biology, genomic data, niche modification, or novel inheritance mechanisms may then enrich evolutionary theory without compromising its underlying stability.

This outcome is entirely compatible with the historical continuity emphasized by Futuyma [24]. A theory capable of incorporating genuinely new knowledge is not exhibiting stress simply because its contemporary form is more complicated than its earlier one. On the contrary, successful extension is evidence of theoretical resilience.

4.4.2. Stable Pluralism

A second possibility is that no single integrated representation is required. Different mechanisms, models, or explanatory strategies may remain appropriate to different biological domains without this constituting theoretical failure.

This possibility is especially important in biology, where multilevel, historically contingent, and heterogeneous systems frequently motivate pluralistic explanation. Mitchell [31] has argued that biological complexity can make integrative pluralism epistemically appropriate rather than merely a temporary symptom of incomplete unification. Similarly,

debates over levels of selection illustrate how multiple explanatory perspectives can remain scientifically informative depending on the biological organization and question under investigation [29].

Predictive Epistemology must therefore avoid treating theoretical unity as an unquestioned norm. The coexistence of several models does not itself constitute increasing complexity in the problematic sense. A pluralistic architecture may be a stable and productive epistemic configuration.

4.4.3. Theoretical Stress

The third possibility is different. Suppose that maintaining the scope or apparent unity of framework T requires a sustained excess of theoretical resources relative to the specified baseline, while a comparable standard of adequacy continues to be preserved.

New domains might then require increasingly independent mechanisms, exceptional cases, restricted assumptions, or conceptual structures whose integration becomes progressively more costly. Under such conditions, the trajectory may indicate theoretical stress.

Even here, the conclusion is not that a scientific revolution must occur. Theoretical stress by itself neither establishes epistemic fragility nor implies that reorganization will follow. Its prospective significance depends on whether it is accompanied by independent signs that the framework's robustness under further relevant demands is declining. A stressed framework may recover through conceptual innovation, reorganize internally, become explicitly pluralistic, or eventually give way to a substantially different architecture.

The contemporary expansion of evolutionary biology is therefore not offered here as evidence that the field has entered such a region. Rather, it provides an appropriate domain in which these alternatives can be distinguished and, at least provisionally, applied. The debate allows us to formulate empirically meaningful questions about whether successive extensions are integrated economically, accommodated through stable pluralism, or associated with a sustained excess cost of maintaining a common theoretical structure.

4.5. A Minimal Diagnostic Illustration: Niche Construction

To make this distinction more concrete, consider niche construction as a minimal qualitative application of the framework. Niche construction is particularly appropriate because organism-driven modification of selective environments can be represented within formal evolutionary models while its broader conceptual significance remains disputed. Laland et al. [32], for example, analyzed niche construction through a two-locus population-genetic model in which environmental resources modified by organisms feed back on subsequent selection. Thus, the incorporation of niche construction does not by itself require abandonment of population-genetic theory or constitute evidence of theoretical stress. At the same time, Uller and Helanterä [33] show that the theoretical significance of niche construction depends on how its causal role is interpreted: both selective and developmental forms can be understood either as compatible with received evolutionary theory or as motivating more substantial conceptual revision.

Within Predictive Epistemology, let p represent an ordered sequence of empirical domains in which organism-induced environmental modification becomes progressively more important for explaining evolutionary dynamics. Let A_0 denote a fixed, domain-appropriate criterion of explanatory adequacy. The connection with constrained Effective Complexity provides a useful way of making this expansion more explicit.

Each position along p may be associated schematically with a set $O(p)$ of empirically relevant observables or explanatory requirements. In the case of niche construction, these may include environmental state variables, organism–environment feedback relations,

inheritance terms, or other quantities whose explanatory relevance becomes explicit as the empirical domain expands [12]. When these requirements accumulate,

$$O(p_1) \subseteq O(p_2) \subseteq \cdots \subseteq O(p_n). \tag{12}$$

Correspondingly, let $\mathcal{R}_T(p) \subseteq \mathcal{R}(T)$ denote the realizations of framework T that remain admissible under the empirical or explanatory requirements associated with position p. Increasing requirements may then restrict the admissible theoretical space:

$$\mathcal{R}_T(p_1) \supseteq \mathcal{R}_T(p_2) \supseteq \cdots \supseteq \mathcal{R}_T(p_n). \tag{13}$$

Here $\mathcal{R}_T(p)$ captures admissibility relative to the empirical or explanatory requirements associated with p, whereas $A(\tau, p) \geq A_0$ imposes the additional requirement that an admissible realization achieve the specified level of performance. These relations should be understood schematically rather than as identifying scientific domains literally with the constraint structures of algorithmic Effective Complexity. Their epistemological significance is that, as additional observables or relations become explanatorily relevant, fewer theoretical realizations may remain admissible. The relevant question for Predictive Epistemology is then whether the minimum complexity required to preserve $A \geq A_0$ increases disproportionately as these empirical requirements accumulate.

This minimal diagnostic illustration provides no grounds for classifying niche construction itself as evidence of an epistemic tipping region. Its formal incorporation into evolutionary models demonstrates at least one route of productive extension: theoretical complexity can increase while yielding corresponding explanatory gains. A diagnosis of theoretical stress would require a different longitudinal pattern, for example, successive expansions or refinements of $O(p)$ restricting the admissible theoretical space in ways that require increasingly independent mechanisms, exceptions, parameters, or auxiliary structures merely to preserve $A \geq A_0$, relative to an explicit baseline. The absence of such evidence here is itself informative. Predictive Epistemology does not infer instability from theoretical novelty or increased complexity alone; it requires a comparative trajectory exhibiting a sustained excess of accommodation cost relative to the specified baseline.

4.6. Relation to Evolutionary Epistemology

The complementary relation of this analysis to evolutionary epistemology can now be made explicit. The issue is no longer only how competing scientific variants arise and are selected. It is also how an established theoretical framework modifies itself in response to a changing empirical and explanatory environment.

Let T_t represent the theoretical framework at time t, and let E_t represent the empirical-explanatory environment confronting it: available observations, experimental results, relevant scales, methodological capacities, and classes of phenomena requiring explanation. Scientific development can then be represented schematically as an adaptive interaction,

$$T_t \leftrightarrow E_t.$$

The relation should not be understood as a literal biological fitness process. Nor is E_t simply an external environment that acts independently upon theory. Scientific frameworks partly determine which phenomena become salient, which measurements are possible, and which explanatory questions are pursued. Nevertheless, the notation captures an essential feature: theories respond to changing empirical demands by modifying their own conceptual and formal structures.

For substantial periods, this adaptation may remain productive. At other times, pluralistic differentiation may provide the most stable response. Predictive Epistemology identifies

a third possibility: the cost of continued accommodation may itself begin to change systematically, providing one potential indicator of epistemic fragility when accompanied by independent signs of declining robustness.

Evolutionary biology is thus reflexive in a precise epistemological sense. The scientific framework that explains adaptation, variation, persistence, and transformation can itself be studied as a framework undergoing adaptive theoretical change. Predictive Epistemology extends this evolutionary perspective by asking whether the trajectory of that adaptation contains prospective indicators that can be tested against subsequent major epistemic reorganization. The biological discussion clarifies how the diagnostic distinctions operate without claiming that evolutionary biology is presently in crisis. Section 5 therefore changes the evidential role of the analysis: rather than illustrating the distinctions in a contemporary scientific domain, it reconstructs a historical trajectory in which the same diagnostic framework can be applied longitudinally.

5. A Worked Longitudinal Reconstruction: The Old Quantum Theory of Atomic Spectra

The niche-construction discussion above was intentionally non-diagnostic: it showed that increasing theoretical content need not constitute theoretical stress. To show more explicitly how the proposed framework can be applied longitudinally, consider a historically reconstructed case: the development of the old quantum theory of atomic spectra. The purpose is methodological rather than confirmatory. Because the subsequent historical outcome is already known, the reconstruction cannot reproduce a genuinely prospective test; it can, however, limit hindsight by fixing the theoretical framework, empirical ordering, adequacy criterion, complexity proxies, and baseline before that outcome is used in the assessment.

For this reconstruction, let T denote the Bohr–Sommerfeld old-quantum-theory framework for atomic spectroscopy, organized around stationary states, transitions between allowed states, quantum conditions, and semiclassical representations of atomic structure. Let $\mathcal{R}(T)$ contain realizations that preserve this general architecture while differing in orbital assignments, quantum numbers, selection constraints, and related auxiliary specifications. The analysis is deliberately restricted to atomic spectroscopy rather than to the full range of problems addressed by the old quantum theory, so that the criterion of adequacy remains sufficiently stable [34,35].

The ordering variable p is fixed by the cumulative spectroscopic demands placed on the framework as its domain of application expanded. Schematically,

$$p_1 : \text{hydrogen spectrum},$$
$$p_2 : \text{fine structure, Stark effect, and ordinary Zeeman effect},$$
$$p_3 : \text{multiplet structure, complex spectra, and selection regularities},$$
$$p_4 : \text{anomalous Zeeman patterns}.$$

This sequence orders the requirements imposed on the framework, not the dates on which every phenomenon was first discovered. In particular, the anomalous Zeeman effect was known earlier; what matters here is the increasing requirement that its empirical regularities be accommodated within the developing quantum-theoretical structure. The ordering is therefore fixed from the historical development of the research programme rather than from a retrospective ranking of which problems eventually proved decisive [35,36].

For the reconstruction, A_0 denotes successful accommodation of the established spectral frequencies, splitting patterns, and transition regularities relevant at each stage, at a level regarded as satisfactory within contemporary spectroscopic practice. This is intentionally narrower than a general criterion of success in atomic physics. Problems of radiation theory,

for example, are not included, because doing so would alter the dimensions along which adequacy is being compared.

The domain-specific proxy κ is operationalized through the proliferation of independently specified theoretical constraints needed to preserve spectroscopic adequacy, including additional quantum-number assignments, selection rules, and auxiliary or semi-empirical prescriptions. Where the same added structure accounts for several phenomena, it is not counted repeatedly; what matters is the need for additional independent commitments rather than syntactic length [36,37].

The early Bohr–Sommerfeld development provides the comparative baseline. Sommerfeld's extension of the Bohr model in 1915–1916 introduced additional theoretical structure, but the same general development yielded several connected explanatory successes, including the fine structure of hydrogen and the Stark and ordinary Zeeman effects. By 1920, the resulting framework had become a central tool of atomic research [34]. This period is therefore used as a baseline of productive extension: complexity increased, but the additional structure generated correspondingly broad explanatory returns. The baseline is selected for this reason, rather than because of what later happened to the theory.

With T, p, A_0, κ, and the baseline fixed in this way, the diagnostic rule can be applied without reference to the subsequent theoretical outcome. Theoretical stress is not inferred from a single difficult phenomenon or from any increase in formal complexity. It requires a sustained departure from the baseline in which continued empirical accommodation increasingly depends on independently specified or increasingly domain-specific theoretical structures.

The later development of atomic spectroscopy provides a qualitative test of this distinction. During the early 1920s, increasingly complex spectra were organized through additional quantum numbers, selection rules, and empirical regularities that did not always follow directly from the mechanical orbital picture [36,37]. These developments were scientifically productive and should not be classified as problematic merely because they enlarged the theoretical apparatus. The relevant question is whether the added structure continued to extend the common framework economically or whether successful accommodation increasingly relied on specialized constructions whose integration with that framework became more difficult.

The anomalous Zeeman effect is particularly informative in this respect. Historical reconstructions describe progressively more complicated attempts to account for the observed splitting patterns and show that these attempts eventually produced serious inconsistencies with the assumed mechanical equations of motion [35]. At the same time, spectroscopic regularities and classificatory schemes continued to organize empirical results even when their relation to the underlying orbital representation had become less direct [37]. The case therefore exhibits a regime in which empirical accommodation could continue through additional structure while the integration of that structure into the common framework became increasingly problematic. The growing difficulty of integrating these additions with the common orbital framework therefore provides a robustness consideration distinct from the complexity proxy itself. Once no admissible realization can satisfy the relevant adequacy requirement, the situation is no longer theoretical stress in the sense defined here but explicit loss of adequacy.

Applied ordinally rather than as a numerical measurement of C_T, the specification therefore distinguishes two trajectories. The earlier period displays productive extension: additional structure generated several related explanatory gains. The later period shows greater reliance on specialized or independently specified constructions in order to accommodate further spectroscopic demands. Relative to the earlier baseline, and under the operationalization fixed above, this provides qualitative evidence of the pattern character-

ized here as theoretical stress. The claim is intentionally limited: the reconstruction does not establish a numerical value of C_T, nor does it imply that every difficulty of the old quantum theory was an instance of theoretical stress.

Only after this classification is made is the subsequent historical outcome introduced. Failed attempts to resolve problems such as the anomalous Zeeman effect contributed to a widely recognized crisis by 1924, and Heisenberg's matrix mechanics in 1925 initiated a major reorganization of the theoretical framework [34]. That subsequent reorganization does not retrospectively establish that the preceding trajectory constituted theoretical stress. The more limited result is methodological: under a framework, empirical ordering, adequacy criterion, complexity proxy, and baseline specified independently of that outcome, the procedure distinguishes an earlier period of productive theoretical development from a later period of increasing accommodation cost that preceded substantial reorganization.

This single historical reconstruction does not validate Predictive Epistemology. It shows more modestly how the framework can be operationalized in a controlled historical setting. A genuinely prospective test would require the same specification to be made in an ongoing scientific episode and evaluated against developments that are not yet known.

6. Scope and Limits: What Predictive Epistemology Can Predict

The proposal developed in the preceding sections is intentionally more limited than the expression Predictive Epistemology might initially suggest. Its aim is not to determine what scientists will believe next, but to investigate whether features of the evolving relation between theoretical complexity and explanatory adequacy provide prospective information about the stability of an existing framework.

A first limitation is that theoretical stress does not by itself establish epistemic fragility or determine what will replace an existing framework. Theoretical stress contributes to a diagnosis of fragility only when supported by independent evidence of declining robustness. Even when such a diagnosis is warranted, several subsequent developments remain possible: the framework may undergo internal conceptual restructuring, recover through the discovery of a more economical mechanism, divide into specialized but stable subframeworks, coexist with competitors, or eventually be replaced by a substantially different alternative. Its prospective object is increasing epistemic fragility, not future theoretical content.

A second limitation is that complexity growth alone is not diagnostically significant. As established in Section 3, Predictive Epistemology evaluates the baseline-relative trajectory of the minimum structural cost required to preserve a specified level of adequacy, rather than theoretical complexity in isolation. A framework may therefore become structurally richer through productive extension without exhibiting theoretical stress.

Third, Predictive Epistemology does not posit a universal complexity threshold beyond which a scientific revolution must occur. In particular, it does not assume that exceeding any fixed value of theoretical complexity necessarily entails theoretical revolution.

Such a claim would conflict with the very conception of complexity on which the framework builds. Effective Complexity is dependent on the regularities regarded as relevant, the level of description adopted, and the context in which those regularities are represented [10]. The earlier formulation of P-Effective Complexity likewise emphasized that the epistemic significance of complexity depends on the model, control parameter, coarse-graining, and explanatory problem under consideration [3,13]. The indicators proposed here must therefore be context-dependent, comparative, and trajectory-based.

A further methodological qualification concerns computability. The algorithmic information measures underlying Effective Complexity are not, in general, directly computable. Gell-Mann and Lloyd explicitly note the uncomputability of algorithmic information content and discuss time-bounded variants as one possible way of obtaining more operationally

accessible quantities [11]. The formal treatment of Effective Complexity by Ay, Müller, and Szkoła likewise proceeds by restricting attention to computable ensembles with computable and finite entropy [12]. Predictive Epistemology therefore does not require the exact computation of Kolmogorov complexity or Effective Complexity in empirical applications. Rather, these quantities provide a formal reference point for constructing explicit, domain-specific proxies for theoretical complexity, such as the number of independently adjusted parameters, auxiliary assumptions, distinct mechanisms, exceptional clauses, computational resources, or description length. The empirical value of the framework will consequently depend on whether such proxies can be specified independently of the theoretical outcome and shown to track meaningful changes in the cost of maintaining explanatory adequacy.

A fourth and equally important limitation is that Predictive Epistemology is not a mathematical reduction of scientific change. The formal expressions introduced above isolate one dimension of theoretical development: the increasing representational cost of maintaining explanatory adequacy. Scientific knowledge, however, develops within communities, institutions, experimental practices, technological infrastructures, and historically changing standards of evaluation. Kuhn's analysis of normal science, anomaly, crisis, and revolution made clear that theoretical transitions cannot be understood independently of disciplinary practices and paradigmatic commitments [38]. Hull's evolutionary account similarly emphasized that conceptual change is inseparable from the organization and interaction of scientific communities [8], while Longino's contextual empiricism showed how evidential reasoning and scientific objectivity depend on social processes of critical interaction rather than on isolated relations between theories and data [39].

Predictive Epistemology therefore isolates a potential structural indicator, not a complete causal theory of scientific change. Institutional authority may delay theoretical transformation; new instruments may abruptly resolve apparent anomalies; changes in methodological values may alter what counts as explanatory success; and scientific communities may retain, abandon, or reorganize frameworks for reasons that cannot be captured by complexity measures alone. These factors do not invalidate the proposed indicator any more than environmental or historical contingencies invalidate the study of other partial predictors. They delimit what it can legitimately claim.

This positioning also clarifies the relation between Predictive Epistemology and broader accounts of scientific change. Kuhn's analysis emphasizes the historical and disciplinary organization of normal science, anomaly, crisis, and revolution [38], while evolutionary epistemology emphasizes the generation, selection, persistence, and transformation of epistemic variants. Predictive Epistemology does not replace these accounts. As clarified in Section 3, it isolates a narrower prospective question concerning the changing structural cost of maintaining adequacy within an established framework.

These specification requirements also establish a minimal condition of empirical risk for the framework. The comparative hypothesis advanced above would be weakened if episodes exhibiting sustained theoretical stress together with independently specified evidence of declining robustness were no more frequently associated with subsequent substantial theoretical reorganization than comparable periods of stable theoretical development. Diagnoses that depended systematically on selecting p, A_0, the complexity proxy, or the comparative baseline only after the historical outcome was known would likewise count against the prospective interpretation of the framework. These conditions allow both false negatives and false positives and therefore place the proposal at genuine empirical risk rather than insulating it through retrospective reconstruction.

Its claim can therefore be stated narrowly. Predictive Epistemology does not predict scientific truth, revolutionary timing, or the architecture of future theories. It investigates whether systematic changes in the cost of preserving explanatory adequacy can provide

prospective evidence that an established theoretical regime is becoming increasingly fragile. The value of the framework depends precisely on maintaining this distinction between a bounded anticipation of instability and an unjustifiably strong prediction of the future of science.

7. Conclusions

This article has developed Predictive Epistemology as an explicit philosophical framework for investigating whether structural changes in a scientific theory may provide prospective information about its changing explanatory stability. Building on an earlier connection between parametric complexity, emergence, and theory change [3,13], the proposal shifts attention from the complexity of a theoretical framework at a particular moment to the trajectory of the theoretical resources required to preserve a comparable level of explanatory or empirical adequacy as scientific demands change. The relevant quantity is therefore not theoretical complexity in isolation, but the lowest structural complexity required by an admissible realization to continue satisfying a specified adequacy criterion. Predictive Epistemology was accordingly defined as the study of structural and informational indicators through which increasing theoretical stress and the approaching loss of explanatory stability may be identified before major theoretical reorganization occurs.

The framework is intended to complement, rather than replace, evolutionary epistemology. Whereas evolutionary accounts emphasize the generation, selection, persistence, and transformation of epistemic variants, Predictive Epistemology concentrates on conditions developing within an established framework before substantial reorganization:

$$\begin{aligned}\text{Changing empirical demands} &\longrightarrow \text{minimum adequate complexity trajectory}\\ &\longrightarrow \text{theoretical stress.}\end{aligned}$$

Epistemic fragility is assessed separately in terms of reduced robustness under further relevant demands. Theoretical stress may serve as a defeasible indicator of such fragility when accompanied by independent evidence of declining robustness.

The crucial claim is not that increasing complexity necessarily signals theoretical decline. Scientific frameworks often become more complex precisely because they successfully explain more phenomena. What matters is whether maintaining a comparable standard of adequacy requires disproportionately increasing theoretical accommodation. Such a trajectory may contribute to a diagnosis of declining explanatory stability when accompanied by independent evidence of declining robustness without determining either when a theoretical transition will occur or what form a successor framework will take.

Evolutionary biology illustrates why this distinction is potentially useful. The contemporary expansion of evolutionary theory can be interpreted in several epistemically different ways: as productive extension, as stable explanatory pluralism, or, under some circumstances, as increasing theoretical stress. Predictive Epistemology does not decide in advance which interpretation is correct. Instead, it reformulates the issue by asking whether new empirical and explanatory domains can be incorporated with proportionate theoretical cost, or whether maintaining an integrated framework progressively demands more extensive conceptual accommodation. In this sense, evolutionary biology becomes a reflexive case in which a theory of evolutionary processes can itself be examined as an evolving epistemic system.

The framework remains programmatic. Its further development will require additional historically informed comparisons, domain-specific operationalizations of theoretical complexity and adequacy, and investigation of whether proposed indicators of theoretical stress genuinely precede major theoretical reorganizations rather than merely accompanying

ordinary scientific growth. This limitation is also what makes the proposal testable rather than metaphorical.

The expression *Predictive Epistemology* should therefore be understood in a deliberately restricted sense. It does not refer to the prediction of future theories or outcomes, but to the prospective identification of structural conditions that may indicate increasing epistemic fragility. In this respect, the framework may also be understood as characterizing a field of epistemic potentialities: constrained possibilities, tensions, and alternative trajectories that remain open prior to theoretical reorganization. The term *predictive* is retained here to emphasize this prospective diagnostic orientation, not to imply deterministic forecasting.

Predictive Epistemology does not seek to predict what science will believe next. It seeks to determine whether the structures through which science currently explains the world are becoming increasingly difficult to sustain.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The author gratefully acknowledges the Santa Fe Institute for providing the intellectual environment in which part of this research was carried out.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Bradie, M.; Harms, W.; Smead, R.; Forber, P. Evolutionary epistemology. In *The Stanford Encyclopedia of Philosophy*, Summer 2024 ed.; Zalta, E.N., Nodelman, U., Eds.; Metaphysics Research Lab, Stanford University: Stanford, CA, USA, 2024. Available online: https://plato.stanford.edu/archives/sum2024/entries/epistemology-evolutionary/ (accessed on 20 October 2026).
2. Scheffer, M.; Bascompte, J.; Brock, W.A.; Brovkin, V.; Carpenter, S.R.; Dakos, V.; Held, H.; van Nes, E.H.; Rietkerk, M.; Sugihara, G. Early-warning signals for critical transitions. *Nature* **2009**, *461*, 53–59. [CrossRef]
3. Fuentes, M. *Complexity, Emergence and the Evolution of Scientific Theories: Towards a Predictive Epistemology*; Springer: Cham, Switzerland, 2025. [CrossRef]
4. Campbell, D.T. Blind variation and selective retentions in creative thought as in other knowledge processes. *Psychol. Rev.* **1960**, *67*, 380–400. [CrossRef]
5. Campbell, D.T. Evolutionary epistemology. In *The Philosophy of Karl Popper*; Schilpp, P.A., Ed.; Open Court: Singapore, 1974; pp. 412–463.
6. Popper, K.R. *Objective Knowledge: An Evolutionary Approach*; Clarendon Press: Oxford, UK, 1972.
7. Toulmin, S. *Human Understanding: Volume I. The Collective Use and Evolution of Concepts*; Princeton University Press: Princeton, NJ, USA, 1972.
8. Hull, D.L. *Science as a Process: An Evolutionary Account of the Social and Conceptual Development of Science*; University of Chicago Press: Chicago, IL, USA, 1988.
9. Renzi, B.G.; Napolitano, G. *Evolutionary Analogies: Is the Process of Scientific Change Analogous to Organic Change?*; Cambridge Scholars Publishing: Newcastle upon Tyne, UK, 2011.
10. Gell-Mann, M.; Lloyd, S. Information measures, effective complexity, and total information. *Complexity* **1996**, *2*, 44–52. [CrossRef]
11. Gell-Mann, M.; Lloyd, S. Effective Complexity. In *Nonextensive Entropy—Interdisciplinary Applications*; Gell-Mann, M., Tsallis, C., Eds.; Oxford University Press: Oxford, UK, 2003; pp. 387–398.
12. Ay, N.; Müller, M.; Szkoła, A. Effective complexity and its relation to logical depth. *IEEE Trans. Inf. Theory* **2010**, *56*, 4593–4607. [CrossRef]
13. Fuentes, M.A. Complexity and the emergence of physical properties. *Entropy* **2014**, *16*, 4489–4496. [CrossRef]
14. Akaike, H. A new look at the statistical model identification. *IEEE Trans. Autom. Control* **1974**, *19*, 716–723. [CrossRef]
15. Forster, M.; Sober, E. How to tell when simpler, more unified, or less ad hoc theories will provide more accurate predictions. *Br. J. Philos. Sci.* **1994**, *45*, 1–35. [CrossRef]
16. Rissanen, J. Modeling by shortest data description. *Automatica* **1978**, *14*, 465–471. [CrossRef]

17. Lakatos, I. *The Methodology of Scientific Research Programmes: Philosophical Papers*; Worrall, J., Currie, G., Eds.; Cambridge University Press: Cambridge, UK, 1978; Volume 1.
18. Scheffer, M.; Carpenter, S.R.; Dakos, V.; van Nes, E.H. Generic indicators of ecological resilience: Inferring the chance of a critical transition. *Annu. Rev. Ecol. Evol. Syst.* **2015**, *46*, 145–167. [CrossRef]
19. Dakos, V.; Carpenter, S.R.; Brock, W.A.; Ellison, A.M.; Guttal, V.; Ives, A.R.; Kéfi, S.; Livina, V.; Seekell, D.A.; van Nes, E.H.; et al. Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. *PLoS ONE* **2012**, *7*, e41010. [CrossRef]
20. Bennett, C.H. Logical Depth and Physical Complexity. In *The Universal Turing Machine: A Half-Century Survey*; Herken, R., Ed.; Oxford University Press: Oxford, UK, 1988.
21. Turner, D.; Havstad, J.C. Philosophy of macroevolution. In *The Stanford Encyclopedia of Philosophy*, Spring 2025 ed.; Zalta, E.N., Nodelman, U., Eds.; Metaphysics Research Lab, Stanford University: Stanford, CA, USA, 2025. Available online: https://plato.stanford.edu/archives/spr2025/entries/macroevolution/ (accessed on 20 October 2026).
22. Laland, K.N.; Uller, T.; Feldman, M.W.; Sterelny, K.; Müller, G.B.; Moczek, A.; Jablonka, E.; Odling-Smee, J. The extended evolutionary synthesis: Its structure, assumptions and predictions. *Proc. R. Soc. B Biol. Sci.* **2015**, *282*, 20151019. [CrossRef]
23. Müller, G.B. Evo-devo: Extending the evolutionary synthesis. *Nat. Rev. Genet.* **2007**, *8*, 943–949. [CrossRef]
24. Futuyma, D.J. Evolutionary biology today and the call for an extended synthesis. *Interface Focus* **2017**, *7*, 20160145. [CrossRef]
25. Mayr, E.; Provine, W.B. (Eds.) *The Evolutionary Synthesis: Perspectives on the Unification of Biology*; Harvard University Press: Cambridge, MA, USA, 1980. [CrossRef]
26. West-Eberhard, M.J. *Developmental Plasticity and Evolution*; Oxford University Press: Oxford, UK, 2003. [CrossRef]
27. Odling-Smee, F.J.; Laland, K.N.; Feldman, M.W. *Niche Construction: The Neglected Process in Evolution*; Princeton University Press, 2003.
28. Jablonka, E.; Lamb, M.J. *Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life*, rev. ed.; The MIT Press: Cambridge, MA, USA, 2014.
29. Okasha, S. *Evolution and the Levels of Selection*; Oxford University Press: Oxford, UK, 2006. [CrossRef]
30. Kauffman, S.A. *The Origins of Order: Self-Organization and Selection in Evolution*; Oxford University Press: Oxford, UK, 1993.
31. Mitchell, S.D. *Biological Complexity and Integrative Pluralism*; Cambridge University Press: Cambridge, UK, 2003.
32. Laland, K.N.; Odling-Smee, F.J.; Feldman, M.W. Evolutionary consequences of niche construction and their implications for ecology. *Proc. Natl. Acad. Sci. USA* **1999**, *96*, 10242–10247. [CrossRef]
33. Uller, T.; Helanterä, H. Niche construction and conceptual change in evolutionary biology. *Br. J. Philos. Sci.* **2019**, *70*, 351–375. [CrossRef]
34. Kragh, H. *Niels Bohr and the Quantum Atom: The Bohr Model of Atomic Structure 1913–1925*; Oxford University Press: Oxford, UK, 2012. [CrossRef]
35. Duncan, A.; Janssen, M. *Constructing Quantum Mechanics: Volume 1: The Scaffold: 1900–1923*; Oxford University Press: Oxford, UK, 2019. [CrossRef]
36. Borrelli, A. The emergence of selection rules and their encounter with group theory, 1913–1927. *Stud. Hist. Philos. Mod. Phys.* **2009**, *40*, 327–337. [CrossRef]
37. Jähnert, M. The formation of a paper tool: Intensity schemes in the old quantum theory. *Arch. Hist. Exact Sci.* **2025**, *79*, 7. [CrossRef]
38. Kuhn, T.S. *The Structure of Scientific Revolutions*, 4th ed.; University of Chicago Press: Chicago, IL, USA, 2012. [CrossRef]
39. Longino, H.E. *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry*; Princeton University Press: Princeton, NJ, USA, 1990. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.