Journal of Applied Mathematics and Physics, 2026, 14(1), 76-107
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Beyond Gödel: Information-Theoretical Limits of Physical Models and the Principle of Optimal Incompleteness

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How to cite this paper: Menin, B. (2026) Beyond Gödel: Information-Theoretical Limits of Physical Models and the Principle of Optimal Incompleteness. *Journal of Applied Mathematics and Physics*, **14**, 76-107.
https://doi.org/10.4236/jamp.2026.141005

Received: December 9, 2025
Accepted: January 2, 2026
Published: January 5, 2026

Abstract

A new conceptual framework is presented that unifies Gödel's incompleteness theorems with practical physical modeling through information-theoretic analysis. The method of variables with finite information content demonstrates that every physical model inherits an irreducible uncertainty, representing a "Gödelian barrier" in physics. Models with too few variables are incomplete and yield high uncertainty, while models with an excessive number of variables become computationally intractable despite theoretical completeness. The concept is validated by a systematic analysis of measurements of six fundamental constants across sixty-five scientific publications from the period 2000-2019. The method provides quantitative criteria for model selection, explains systematic discrepancies in precision measurements, and establishes fundamental limits to measurement accuracy independent of improvements in instrumental technology. This work offers researchers a practical tool for assessing model adequacy and understanding why certain physical constants resist precise determination.

Keywords

Information Theory, Model Uncertainty, Physical Constants, Gödel's Incompleteness, Comparative Uncertainty, Measurement Limits, Phenomenological Group, Optimal Modeling, Metrology

1. Introduction

For centuries, the pursuit of science has been driven by a quest for elegant simplicity. The greatest leaps—from Newton's laws to Maxwell's equations, from Einstein's relativity to quantum mechanics—reveal a deep conviction: the universe speaks a language of mathematical beauty, and our task is to decode it [1] [2]. Yet in the 21st century, this elegant picture shows cracks. Despite astonishing advances in computing, instrumentation, and theory, something isn't adding up. When we try to pin down the most fundamental constants of nature, different methods keep giving us different answers—discrepancies that stubbornly refuse to fade away [3]-[5].

Take the so-called "Hubble tension" [6] [7]. Depending on how fast the cosmos is expanding, you get numbers that are disagreeable. It's not a minor glitch; the gap is larger than our stated uncertainties should allow. The same story plays out with something as foundational as the gravitational constant. Over the past two decades, top labs worldwide have published values that scatter well beyond their reported error bars [8]-[10]. This isn't just about better gear or tighter procedures. Something deeper seems off.

The usual fix involves doubling down on what we already do: refine the experiment, collect more data, apply fancier statistics, hunt down hidden systematic errors [11]-[13]. Even the gold standard for reconciliation—the CODATA committee's careful blending of results using Bayesian and least-squares methods [14] [15]—can't fully escape a whiff of subjectivity. Sometimes, to make the numbers agree, uncertainties get quietly stretched [16]. It feels less like solving a puzzle and more like forcing the pieces to fit.

Then there's Gödel. In 1931, the Austrian mathematician Kurt Gödel dropped a logical bombshell: his incompleteness theorems [17] [18]. In any formal system robust enough to handle basic arithmetic, he showed, there will always be true statements that can't be proven from within. The system also can't prove its own consistency. For a long time, this was seen as a fascinating quirk of pure mathematics—a mind game with little to say about the tangible world [19] [20].

But lately, that view has been shifting. A growing chorus wonders: what if Gödel's limits aren't just about symbols on a page? What if they reflect a genuine boundary embedded in physical reality or at least in our capacity to grasp it? [21]-[23]. Freeman Dyson speculated that such constraints might forever bar the door to a final "theory of everything" [24]. Stephen Hawking once leaned the same way before hedging his bets [25]. Roger Penrose has gone further, arguing that Gödel-like incompleteness might actively shape quantum mechanics and even consciousness [26] [27].

Still, for all the philosophical weight, a practical bridge has been missing. How do you move from abstract "unprovability" to the gritty, real-world headache of, say, measuring a constant to the tenth decimal? The question hangs there: is this incompleteness written into the universe, or is it just a flaw in our lenses?

While these debates simmered, another field was quietly reshaping everything. Information theory, born from Claude Shannon's 1948 masterpiece [28], didn't just revolutionize communications. It seeped into genetics, neuroscience, cryptography—becoming a universal grammar for complexity [29]-[31]. And it didn't stop at physics' door. Léon Brillouin famously tied entropy not just to heat, but to a lack of knowledge—treating information as a physical quantity from the start

[32]. Then came Rolf Landauer with his elegant, devastating principle: erasing a bit of information isn't free. It necessarily dissipates heat [33]. Information wasn't just like a physical entity; it was one. The connection had ceased to be a metaphor.

Subsequent work began applying the lens of information theory to various branches of physics. Jacob Bekenstein, for instance, calculated the ultimate information "capacity" of a spatial region—roughly speaking, how many bits you can cram into a given volume [34]. Seth Lloyd went further, estimating the total computational power of the Universe by envisioning it as a giant, albeit finite, quantum computer [35]. On the experimental front, a quiet revolution was taking place: physicists achieved quantum teleportation and launched the first prototypes of quantum computers, demonstrating tangibly that information in the micro-world behaves by different rules [36] [37].

Yet here's the curious thing: amid all this expansion, one corner remained largely untouched. Information theory had scarcely addressed the most fundamental problem—how to gauge the intrinsic, unavoidable uncertainty of a physical model itself. Sure, we had handy statistical tools like the Akaike Information Criterion (AIC) or its Bayesian counterpart (BIC) to choose between competing equations [38] [39]. But these tools worked "after the fact", during data processing. They didn't answer the core question: where does this uncertainty even come from? Could it be rooted in something deeper than mere instrument error?

This brings us to the very foundation of the entire edifice—the system of units. The International System (SI), officially born in 1960 and undergoing a radical reboot in 2019 [40] [41], rests on seven pillars: the meter, kilogram, second, kelvin, ampere, candela, and mole. Everything else is derived. This set is not a tablet of divine commandments but a historically evolved contract, reflecting how the human mind carves up reality into manageable pieces [42] [43]. And like any contract, it imposes its own rules of the game. Alexander Sonin aptly showed that the dimensions of physical quantities form an abelian group—meaning they obey strict mathematical rules, which opens up intriguing possibilities for analysis [44].

From an information perspective, the system of units transforms into a kind of "communication channel" between the phenomenon and the researcher [45]. Any model we create is a set of variables selected from this limited alphabet. And here is the crucial point: the finiteness of this alphabet—just seven independent "letters"—means that any description of reality we formulate will be inherently incomplete. We simply cannot express in words that for which we have no words. This is that fundamental limitation, baked into the very foundation of our understanding.

A recent proposal introduces an approach based on the concept of a Finite Information Quantity (FIQ) [46]-[48]. This framework uses the mathematical apparatus of information theory to put a number on the inherent limitations of physical modelling. Its core idea is refreshingly direct: each variable in a model carries only a finite amount of information about the observed phenomenon. The model's total informational content is thus capped by the number and type of variables it includes.

The FIQ approach rests on five axioms. The first states that a researcher selects variables for a model from a specific system of units. The second posits that a model's individuality is defined by its choice of base quantities from that system, forming what is called a Group of Phenomena (GoP). The third defines variables as finite information quantities that take values from the set of real numbers. The fourth asserts that a model contains a finite amount of information simply because the number of variables is limited, and each carries a bounded portion of information. The fifth, and most debated axiom, proposes that any variable is selected by a conscious observer on an equiprobable basis. We acknowledge that this equiprobability postulate may appear counter-intuitive, as experienced researchers clearly do not choose variables at random but rather rely on scientific culture, knowledge, and intuition. However, this postulate reflects a deeper epistemological consideration about the initial symmetry in theory formation before empirical data accumulates. A detailed justification of this axiom, grounded in historical examples from the development of physical theories and the philosophy of science, is provided in Section 4.

From these axioms, a quantitative criterion emerges for gauging a model's a priori uncertainty—an uncertainty that depends solely on the qualitative and quantitative set of variables chosen. This yardstick, dubbed the comparative uncertainty, lets us estimate the minimally achievable accuracy of a model before any experimental measurements or computational runs begin.

Modern physics is grappling with a handful of fundamental problems that resist satisfactory resolution through traditional means. The aforementioned Hubble tension is a prime example [49] [50]. The cosmic distance ladder method, built on observations of Cepheids and Type Ia supernovae, gives a Hubble constant value around 73 kilometers per second per megaparsec. Meanwhile, analysis of the Cosmic Microwave Background (CMB) within the standard ΛCDM cosmological model points to a value near 67 of the same units [51]. The difference is statistically significant and stubbornly resists explanation by known systematic errors.

A strikingly similar story unfolds with the gravitational constant, G. Despite being the first physical constant proposed in scientific history, the precision of its measurement remains curiously poor compared to other fundamental constants [52] [53]. Different techniques—torsion balances, angular acceleration, free-fall deflection, electrostatic compensation, Fabry-Perot resonators, balance scales, and atomic interferometry—yield results whose spread dramatically overshadows their stated uncertainties [54]-[60]. The constant seems to defy our attempts to pin it down.

The aim of the present work is to establish a quantitative link between Gödel's abstract theorems on the incompleteness of formal systems and the concrete limitations of physical modeling and measurement. We propose that the information-theoretic constraints inherent to any physical model—arising simply from the finite number of variables it includes—can be viewed as a physical analogue of Gödelian incompleteness. Building on the Finite Information Quantity (FIQ) approach, we derive a quantitative criterion of "optimal incompleteness." This criterion makes it possible, for each class of phenomena, to determine the optimal number of variables that strikes a balance between descriptive completeness and computational feasibility. At the same time, to avoid misinterpretation, it should be clearly noted that the proposed framework uses Gödel's theorems as a powerful physical analogue, rather than as a direct mathematical application of formal logic to physical systems.

We apply this framework to a systematic analysis of measurement results for six fundamental physical constants—Planck's constant, Boltzmann's constant, the Hubble constant [61] [62], and the gravitational constant—drawn from sixty-five scientific publications spanning the years 2000–2019, evaluating them through the lens of informational completeness.

The results of our analysis lead to several key conclusions. First, each physical law is characterized by a specific degree of informational incompleteness that cannot be eliminated by any improvement in measurement technology or data-processing mathematics. Second, this incompleteness is not a flaw in the law but a fundamental property, analogous to Gödelian incompleteness in formal systems. Third, an optimal degree of model complexity exists, where the best compromise is achieved between descriptive accuracy and practical applicability.

The structure of this work is organized as follows. Section 2 presents the mathematical foundations of the finite-information-quantity approach, derives the formula for calculating a model's comparative uncertainty, introduces the concept of optimal incompleteness, and establishes a criterion for determining the optimal number of variables in a model. Section 3 applies this methodology to a systematic analysis of measurements of fundamental physical constants. Section 4 discusses the philosophical and methodological implications of the results. Section 5 contains the conclusions and proposals for future research.

2. Fundamental Information Structure of a Physical Model

Every physical model begins not with observation or experiment, but with the fundamental act of distinction performed by an observer. Before numerical values, laboratory setups, statistical procedures, or data-processing algorithms come into play, the researcher takes a first, crucial step: choosing which quantities and relationships between them are deemed essential for describing a phenomenon. This choice is neither arbitrary nor physically predetermined; it is shaped by the observer's attentive focus—their cognitive capacity to isolate and differentiate. This is precisely why a model can never be infinite: any description of reality has a finite information capacity, determined by the number of independent measurable variables, each carrying only a finite amount of information.

This perspective aligns with a key theme in 20th-century physics, which steadily dismantled the illusion of infinite measurability. Einstein's theory of relativity revealed the bounded structure of spacetime [63]; Heisenberg's quantum mechanics exposed the inherent limitations of the measurement act itself [64]; subsequent work by Shannon [28], Landauer [33], Bekenstein, and Hawking [34] [25] established that the information capacity of any physical object—and any information channel—is finite. On this trajectory, an information-based modeling approach grounded in the finiteness of distinguishable differences emerges as a natural extension of fundamental physical and philosophical thought.

This leads us to the first key concept: the Finite Information Quantity (FIQ) [65]. An FIQ is a variable—such as a scalar time parameter, a universal constant, a one-dimensional component of position or momentum, or a dimensionless number—that takes values from the set of real numbers R. As developed in later articles [46]-[48], an FIQ represents the minimal informational unit associated with a specific measurable quantity within a chosen system of units. It is not a physical discreteness like energy quanta, nor is it a technical limit of an instrument. Rather, an FIQ is the minimally distinguishable state of a quantity within a model formulated by an observer. Since a system of units contains a finite number of base variables and a finite set of permissible dimensional combinations, the number of FIQ in any well-constructed model is always finite. A variable with finite information quantity is not a quantity "approximated" for technical reasons; it is a fundamental characteristic of its description within the chosen framework. Thus, the FIQ captures the minimal structure of distinguishability possible in a given theoretical frame.

The next concept is the parameter μ is the number of dimensionless FIQ in a system of units. For the SI system, one can calculate $\mu_{SI} = 38,265$ [46]. It is important to note that all subsequent reasoning and derived formulas apply to models containing any FIQ, whether dimensional or dimensionless [48]. The value μ_{SI} expresses the quantity of independent dimensionless combinations (dimensionless FIQ) that can be formed based on the seven SI base quantities. In other systems of units with a different number of base quantities, the value of μ changes accordingly. However, the principle remains unchanged: μ is always finite. It is not an empirical parameter derived from experimental data; it is determined solely by the dimensional structure of the system of units. This is precisely why μ serves as a fundamental characteristic of any model constructed within that system.

These facts carry profound implications. Since μ is finite, no model can achieve infinite precision. Since μ is finite, no model can admit infinitesimal distinguishability. And since μ is finite, this informational limit on accuracy cannot be overcome by improving instruments, extending observation time, or refining mathematical techniques. These conclusions resonate with the structure of limitations emerging from information-based theories of measurement [66], as well as with the entropy bounds established in the work of Bekenstein [5] and Hawking [6], where the information capacity of a physical system is tied to its geometric properties.

The choice of a GoP (Group of Phenomena) defines the structure of dimensional relationships between variables. A GoP is not a physical group in the strict algebraic sense, but rather a set of measurable quantities united by a common dimensional structure. The term GoP aligns fully with the dimensional analysis pioneered by Bridgman and Barenblatt, yet within the information-based method, it acquires new significance: it becomes the bearer of the ultimate structure of distinguishability.

Let z' denote the number of FIQ in the chosen GoP, and β' is the number of base quantities in that GoP. The number of informational degrees of freedom within the GoP is then given by the difference $z' - \beta'$. This value characterizes the depth of the distinguishability structure permitted by the very nature of the class of phenomena under study. If the GoP is complex—for instance, simultaneously involving electromagnetic, thermodynamic, and mechanical parameters—the difference $z' - \beta'$ becomes large, and the model's minimal uncertainty rises accordingly. If the GoP is simple—a purely kinematic process, for example, the number of dimensional combinations is smaller, and the potential distinguishability is higher.

But the nature of the phenomenon is only half of the structure. The other half is what the observer chooses to include. If a model incorporates z'' (the number of FIQ written into the model) and β'' (the number of base quantities written into the model), then the informational structure of the model is determined by the difference $z'' - \beta''$. This quantity reflects how finely the observer chooses to detail the description. If too few variables are included, the model remains coarse and its uncertainty grows. If too many variables are included, the model becomes overloaded; the possible informational combinations become insufficient to sustain all distinctions, and uncertainty again increases.

Thus, it is precisely the balance between $z' - \beta'$ (the structure of the phenomenon) and $z'' - \beta''$ (the structure of the observer's attention) that determines the ultimate precision achievable in modeling.

This fundamental relationship is expressed in the formula for the model's limiting absolute uncertainty, Δ [46]-[48]:

$$\Delta = S \cdot \left[\frac{z' - \beta'}{\mu} + \frac{z'' - \beta''}{z' - \beta'} \right], \tag{1}$$

where S is the range of variation of the primary quantity under study. Formula (1) is the cornerstone result of the informational approach, representing a deep correspondence principle. It states that the absolute uncertainty is determined solely by the structure of the GoP and the structure of the chosen model and does not depend in any way on instruments or measurement methods.

It is precisely this implication that makes formula (1) so significant: it shifts the problem of accuracy from the domain of engineering into the domain of knowledge structure.

The model's comparative uncertainty is defined by the ratio [46]:

$$\varepsilon = \frac{\Delta}{S}, \tag{2}$$

and it is this quantity that serves as a universal structural parameter of the model. Because ε reflects informational structure rather than instrumental properties, the accuracy of a model can only be meaningfully evaluated by comparing quantities of the same nature. This is why the optimality criterion takes the form

$$\frac{\varepsilon_{\exp}}{\varepsilon_{\mathrm{opt}}}, \tag{3}$$

and only in this form does it carry rigorous meaning. Here, $\varepsilon_{\exp}$ is the comparative uncertainty achieved in the experiment.

If the ratio (3) tends toward unity, the model is optimal: the experimental uncertainty has reached the informational limit imposed by the GoP. If, however, (3) is much greater than one, the model is structurally inconsistent with the phenomenon—even if the instruments themselves report impressively low relative uncertainties $r_{\exp}$.

For practical interpretation, however, a non-rigorous auxiliary relation is introduced:

$$r_{\exp} \gtrsim r_{\mathrm{GOP}}, \tag{4}$$

where r_{GOP} —is the minimum relative uncertainty, equivalent to $\varepsilon_{\mathrm{opt}}$, but expressed in standard metrological units. We cannot directly compare $r_{\exp}$ with $\varepsilon_{\mathrm{opt}}$ because they belong to different domains: ε reflects the informational structure of the model, while r describes the uncertainty of the measurement process itself.

Yet it is precisely relation (4) that bridges informational theory with classical metrology—and therein lies its utility.

The informational structure of a model, captured by formulas (1) - (4), does not arise from specific physical laws or statistical assumptions; it precedes them. The nature of the phenomenon determines the depth of the GoP, the observer chooses the level of detail, and the system of units fixes the available information capacity through the parameter μ. It is this threefold structure that imposes finiteness on any model.

This finiteness—expressed through the finite number of FIQ and the finiteness of μ—shatters the illusion that instrument refinement can increase accuracy indefinitely. In reality, once $\varepsilon_{\mathrm{opt}}$ is reached, further reduction in uncertainty becomes impossible without fundamentally changing how the phenomenon is described. What appears in classical metrology as a technical limit is, within the informational framework, revealed as a structural limit.

This structural limit explains why attempts to reduce the uncertainty in measuring fundamental constants encounter sharp asymptotic barriers. For instance, measuring the gravitational constant G employs several methods: torsion balances, atomic interferometers, and pendulum setups. Each method corresponds to its own GoP, its own dimensional structure, and consequently its own inherent $\varepsilon_{\mathrm{opt}}$ [46]-[48]. Therefore, the discrepancy between results from different laboratories is not an "anomaly" or an "unexplained error" but a consequence of the structural differences between their GoPs.

Traditional metrology lacks the means to formalize this difference; the informational method provides it. Formula (1) demonstrates that the minimum uncertainty of different methods inevitably differs because their values for ($z' - \beta'$) and ($z'' - \beta''$) differ.

A similar situation is observed in measurements of Planck's constant h [61] [66]. Spectroscopic methods, Josephson standards, quantum electrical metrology, and watt balances—all belong to different GoPs. Their ultimate achievable precision is, by definition, different, even under ideal experimental conditions.

This notion aligns with the view in quantum measurement theory that Heisenberg's uncertainty principle [2] is not a result of technical limitations but a consequence of the structure of description. The informational method reveals that similar constraints emerge even in classical physics, where arbitrary accuracy might seem attainable.

What appears in quantum mechanics as a fundamental quantum uncertainty becomes, within the informational approach, a specific case of a more general rule: accuracy is bound by the structure of distinguishability. Measurement is not the retrieval of a pre-existing value but the construction of a distinction between states, made possible within the confines of a model.

In this context, μ serves as a universal parameter of distinguishability. It defines the maximum number of independent dimensionless complex variables that can be constructed within a system of units. If μ were infinite, a model could be arbitrarily detailed. Yet μ remains resolutely finite—and this finitude itself marks a fundamental boundary for what can be known.

The philosophical weight of this limit is considerable. Because μ derives from the system of units—a framework devised by the observer—it turns out that measurement precision hinges not just on the phenomenon being studied, but equally on the conceptual toolkit of the person studying it.

In the end, what we call informational uncertainty belongs not to the device, but to the encounter between observer and observed. It reflects the relationship itself. This echoes a perspective found in modern quantum measurement theory [11] and aligns with Carlo Rovelli's relational quantum mechanics [67], where outcomes are never absolute but always emerge from a specific interaction.

Yet the informational approach extends this linkage to classical physics as well: even in the absence of quantum effects, it is the observer who defines the structure of distinguishability. They choose the GoP, they select the set of variables, they decide on the system of units. These choices shape the model's structure—and thereby set the ceiling for its possible precision.

This implies that the optimal model is not the most detailed one. It is the model with an optimal number of variables, the one for which ε_{opt} reaches its minimum possible value. The result dispels a common misconception that accuracy grows with model complexity. The opposite is true: excessive complication increases uncertainty, just as excessive simplification does.

The informational method makes this statement rigorous. For any GoP, there exists an optimal value of ($z'' - \beta''$) at which the model achieves its fundamental accuracy. This optimality is not a heuristic; it is calculated from the structure of the phenomenon itself. That is why the ratio $\varepsilon_{exp}/\varepsilon_{opt}$ serves as the primary tool for evaluating models.

If $\varepsilon_{exp} \approx \varepsilon_{opt}$, the model matches the phenomenon. If ε_{exp} is substantially larger than ε_{opt}, the model is inadequate—regardless of how precise the instrument is or how small the statistical error may be.

This distinction allows us to separate two natures of uncertainty: the statistical (characterized by r_{exp}) and the structural (characterized by ε). It is the structural uncertainty that is fundamental, as it sets the limit of distinguishability before an experiment even begins.

In this context, the auxiliary relation $r_{exp} \gtrsim r_{GOP}$ serves a meta-function. It does not define optimality, but it allows the informational method to be integrated into traditional metrology. A researcher accustomed to working with relative uncertainties can compare rexp to r_{GOP} to gauge how close a result is to the fundamental boundary—yet this translation does not alter the core of the analysis.

It is essential to clarify why relation (4) is characterized as "non-rigorous auxiliary" rather than a fundamental criterion. The comparative uncertainty ε operates within the informational structure of the model itself—it is a dimensionless measure reflecting the ratio of inherent uncertainty to the range of variation, both defined within the theoretical framework. In contrast, the relative uncertainty r belongs to the domain of experimental metrology, where it quantifies the ratio of measurement uncertainty to the measured value, typically expressed in conventional units (parts per million, percentages, etc.).

These two quantities inhabit fundamentally different conceptual spaces: ε characterizes the model's structure before any measurement is performed, while r characterizes the outcome of an actual measurement process. The auxiliary relation (4) serves as a practical bridge between these domains, allowing researchers familiar with traditional metrological language to assess their results against informational limits. However, this translation is not mathematically rigorous because it conflates two distinct types of uncertainty—one structural and a priori, the other statistical and a posteriori.

The rigorous criterion remains (3), where both quantities belong to the same informational framework. Relation (4) should be understood as a pragmatic tool for interpretation rather than a fundamental law. Its utility lies in making the informational approach accessible to the broader scientific community without requiring a complete reformulation of existing metrological practices.

The fundamental nature of the ε-approach is confirmed by the invariance of formula (1) under changes to the system of units. Whether switching from SI to CGS or any other system, μ will change, z' and β' will change, but the very structure of the limiting uncertainty remains preserved [47]. This is analogous to dimensional covariance: the model takes on a different form, yet its informational structure stays unchanged.

Furthermore, because the GoP is defined by the observer, formula (1) takes on aspects of a participatory principle: the observer determines which distinctions will be possible. This is not subjectivism; it is the recognition that a model is, at its core, a mechanism for making distinctions. Reality does not "deliver" information prepackaged; information arises as a structure of distinguishability defined within the model.

This philosophical line aligns with modern informational models of gravity [7]-[9] and with ideas proposing spacetime structure as a manifestation of informational correlation. Formula (1) can be viewed as a specific case of a more general principle: distinguishability is the fundamental structure of physical description, and a measurement is the realization of that distinguishability in a concrete experiment.

From these considerations, it becomes clear why μ cannot approach infinity. An infinite μ would imply infinite dimensional freedom, and consequently the possibility of infinitely precise distinction. However, the structure of dimensions is finite, and a system of units fixes the number of base quantities a priori. As long as physics is described by a finite number of dimensions, μ remains finite and cannot be increased arbitrarily.

This means the ultimate accuracy of any measurement is tied to the fundamental characteristics of the physical theory—specifically, to its dimensional structure. This brings the informational approach closer to the theoretical limits discussed in the works of Ng, van Dam, and Amelino-Camelia [68] [69], where fundamental accuracy limits are analyzed using quantum-gravitational arguments. Yet, unlike those approaches, the informational method does not require new physical assumptions: it proceeds from the structure of the model itself, not from hypotheses about the quantum nature of spacetime.

On this basis, an important conclusion can be drawn: the informational limit ε_{opt} is a structural analogue of a quantum constant. It is not introduced manually, is not a property of an instrument, and is not determined by statistics. It arises inevitably from the structure of distinguishability, defined by the GoP, the choice of variables, and the number of FIQ in the system of units.

Once ε_{opt} has been calculated, it becomes clear that further reduction of uncertainty is impossible without altering the GoP. This explains the persistent phenomenon of accuracy "saturation" in experimental physics: when results cease to converge, additional precision stops yielding new information.

This reasoning makes it clear that expression (1) is not a specialized formula but reflects a universal structure of any physical model arising at the junction of three fundamental levels: the structure of the phenomenon (GoP), the structure of the model (choice of variables), and the structure of the system of units (μ). It is the coherence of these three levels that determines the ultimate distinguishability of any quantity and, through it, the fundamental accuracy of measurements. Such an approach bridges classical ideas of dimensional analysis—beginning with the works of Bridgman and Buckingham [70] [71]—with informational concepts developed by Brillouin, Jaynes, and Cox [72]-[74]. In this synthesis, the ultimate uncertainty ceases to be a technical characteristic of an instrument and becomes a quantitative expression of the very structure of knowledge.

Formula (1) demonstrates that the minimum uncertainty inevitably follows from the finiteness of the number of dimensionless combinations μ allowed by the system of units. This aligns with Bridgman's view that a physical quantity exists only within the confines of permissible measurement operations [70], and with Buckingham's idea that all physical models reduce to a limited number of independent dimensionless groups [71]. However, the informational approach generalizes these classical principles: μ is treated not as a technical parameter of dimensional structure, but as the ultimate informational capacity of the system of units. It plays the same role as the ultimate entropy capacity of a physical system in the work of Bekenstein and Hawking [25] [34]: it fixes the fundamental number of independent distinctions available to an observer within a given description.

This substantially changes the interpretation of measurement error. In traditional metrology, the uncertainty rexp is viewed as a characteristic of statistical fluctuations and engineering limitations. But in the informational interpretation, the fundamental part of the uncertainty is determined by the structure of the GoP, and the performed experiment merely realizes a portion of the available distinguishability. Therefore, the ratio εexp/εopt is not merely a criterion for experimental quality, but a criterion for the model's correspondence to reality.

If $\varepsilon_{exp}/\varepsilon_{opt} \to 1$, the experiment has reached its informational limit—further reduction of uncertainty is impossible without changing the GoP or the variable structure. If $\varepsilon_{exp}/\varepsilon_{opt} \gg 1$, the model is inadequate regardless of the level of technology. Similar conclusions are found in modern quantum metrology, where fundamental accuracy is limited not by noise but by the structure of the state space [72]. However, the informational framing is broader: it applies not only to quantum quantities but to classical models of any nature.

An important consequence of formula (1) is that the ultimate uncertainty decreases as μ increases, reflecting the growth in the informational resolving power of the system of units. This behavior is consistent with Brillouin's ideas connecting measurement to the volume of distinguishable phase-space states [66], and with Jaynes' notion that any physical model should be considered a procedure for selecting an optimal structure of distinguishability [73]. Here, μ acts as a metric for the complexity of the system of units: as the number of independent dimensional directions grows, so does the number of potential distinctions that can be introduced into a model. But simultaneously, the complexity of the GoP also increases, leading to new constraints on distinguishability.

This balance is directly reflected in the structure of formula (1): an increase in μ reduces the first term, but an excessively broad GoP increases the minimum uncertainty through the growth of $(z' - \beta')$. Thus, there exist fundamental limits to expanding the spaces of distinguishability, analogous to the limits on increasing the degrees of freedom when constructing effective theories in quantum physics [74].

Another crucial aspect is that excessive detail in a model can actually erode its distinguishability. This phenomenon, known in statistical physics (model overfitting, excessive entropy complexity), receives a precise quantitative formulation here: too large z'' increases the expression ($z'' - \beta''$), reduces distinguishability, and raises the fundamental uncertainty. In this sense, the informational limit serves as an analogue of the optimal-complexity principle (Occam–Jaynes), where model quality is determined not by the sheer number of parameters, but by how well the description's structure matches the number of distinguishable physical states [75]. A model should be just complex enough to capture the phenomenon's structure, and no more. Formula (1) quantifies this principle.

The informational approach also clarifies several issues that remain murky in traditional metrology. For example, the often-discussed challenge of reconciling measurements of the gravitational constant G is not just due to different experimental setups but primarily stems from the different GoPs used across experiments. If GoPs are not aligned, then the minimal εopt values for different models are simply incommensurable, leading to systematic discrepancies in results. This effect resembles the known difficulties in transferring quantum gauge constants between different measurement protocols [76], but within the informational interpretation, it becomes a universal law: a mismatch in GoPs inevitably yields mismatched results, regardless of statistics. Similar conclusions appear in the work of Knuth and other authors developing the logical-informational foundations of physics [77] [78].

An important philosophical dimension of the informational approach lies in its treatment of the observer. As noted by Heisenberg [79] and Wheeler [80], observation is not a neutral act; it determines the form of distinguishability. Within the ε-framework, this notion acquires a strict quantitative expression: the observer's influence manifests through their choice of z'', β'', and the GoP. Thus, the limiting absolute uncertainty Δ is not a sign of cognitive limitation but a consequence of the observer's active participation in constructing the model. One cannot distinguish more than the structure of attention allows, and one cannot measure more than the GoP permits. In this sense, formula (1) represents a generalization of Wheeler's "it from bit" principle [79]: physical quantities exist only within the context of a distinguishability structure created by the observer.

This perspective allows us to reinterpret the nature of fundamental constants. Their values and the achievable accuracy of their measurement are determined not only by the physical nature of the processes involved but also by the structure of the GoP within which they are defined. This aligns with modern research on entropic and holographic bounds [34] [74] [80]-[83], which shows that limits of resolvability are dictated by the informational structure of state space. In the informational approach, fundamental constants emerge as parameters that define the density of distinguishability within the corresponding GoP; their "unimprovable" uncertainty r_{GOP} is a direct consequence of expression (1).

Consistently applying the ε-approach also reshapes our understanding of experimental error. Error ceases to be a deviation from a "true" value and becomes a measure of the mismatch between two structures of distinguishability: that of the model and that of the phenomenon. Consequently, the ratio εexp/εopt serves as a metric of coherence: if it is large, the model is inadequate; if it is small, the model is optimal. This allows for evaluating the quality of models and experiments independently of statistical data processing. Similar ideas are being developed in modern informational measurement theory (quantum Cramér–Rao bounds, Holevo bounds) [76] [84], although there they pertain only to quantum quantities. The ε-approach, by contrast, is universal.

Formula (1) reveals yet another fundamental symmetry. It remains invariant under the choice of a system of units: changing μ alters the numerical values, but not the structure of the relations. This reflects the informational covariance of models: the physical content is invariant under transformations of the unit system, much as the laws of general relativity are invariant under the choice of coordinates [85]. Dimensions may change, but the structure of distinguishability does not. This invariance ensures the consistency of physical models constructed in different dimensional systems, provided the GoP is correctly recalculated.

The fundamental conclusion is this: *the minimum uncertainty* Δ *and its relative form* $\varepsilon = \Delta/S$ *are universal characteristics of the model's informational structure*, *not of experimental technique*. They fix the ultimate number of distinguishable states accessible to the observer through the chosen GoP. The model's structure determines how closely an experiment can approach this limit. The ratio $\varepsilon_{\text{exp}}/\varepsilon_{\text{opt}}$ is a strict criterion of optimality, while the auxiliary relation $r_{\text{exp}} \gtrsim r_{\text{GOP}}$ serves merely as a practical tool for interpretation.

The informational approach shows that the physical reality accessible to an observer is shaped at the intersection of the phenomenon's structure and the structure of attention. The finiteness of μ, the finiteness of z', z'', and the boundedness of the GoP rule out the possibility of zero uncertainty—but it is precisely this finiteness that makes a physical theory possible at all. Formula (1) expresses the fundamental boundary of distinguishability—a boundary without which measurement, models, and physics itself could not exist. It acts as an informational correspondence principle, uniting classical dimensional analysis [71], fundamental ideas of information physics [86], modern entropy bounds [34], quantum metrology [76], and the logical-informational foundations of contemporary models [87].

The example presented below is intentionally instructive and didactic. This choice is motivated by the need to explicitly demonstrate the main features of the application of the FIQ-method. Consider the motion of a simple pendulum: a ball of mass m, suspended in a gravitational field on a weightless rigid rod of length l. The motion is assumed to take place in a single plane. Let the pendulum be subjected to a friction force R_{fr}, which is proportional to the velocity v of the body, $R_{fr} = -A \cdot v$, where A is a proportionality coefficient determined by the properties of the surrounding medium and the shape of the body. Let x denote the angular deviation of the pendulum from the vertical direction.

The dependence of the dimensionless maximum amplitude $x_{\max}$ of the pendulum can be represented in the following form:

$$x_{\max} = \varphi\left(a = \frac{A}{m}\left(\frac{l}{g}\right)^{1/2}, \Delta p = \frac{R_{fr}}{mg}\right), \quad (5)$$

where g is the acceleration due to gravity.

This transformation reveals the similarity laws governing the system: for given boundary conditions, the dependence of x remains the same for different values of m, l, g, and A, provided that the dimensionless combinations a and p have identical numerical values. These dimensionless complexes do not depend on the choice of the System of Units. The functional form of φ can be determined either analytically, by solving the equation of motion, or experimentally.

This approach significantly reduces the scope of required investigations. Instead of exploring the full four-dimensional parameter space, it is sufficient to study the system as a function of two dimensionless parameters. In other words, the results obtained for a pendulum under one set of conditions can be transferred to other cases by a simple change of scale.

An additional advantage arises in numerical simulations of the dimensionless equations of motion. In this case, the variables involved typically do not differ by many orders of magnitude, a situation that can easily occur when dimensional equations are solved with an inappropriate choice of units.

According to equation (1), for the group of phenomena $\mathrm{GOP_{SI}} = \mathrm{LMT}$, $\varepsilon_{\mathrm{opt}} = 0.0048$, a number of FIQs inherent in $\mathrm{GoP_{SI}}$ [48], $\gamma_{\mathrm{GoP}} = z' - \beta' = 91$, an optimal number of FIQs inherent in a model, $\gamma_{\mathrm{mod}} = z'' - \beta'' = 2$. Then the comparative uncertainty ε_1 due to the finiteness of the physical-mathematical model is

$$\varepsilon_1 = \frac{z' - \beta'}{\mu_{\mathrm{SI}}} + \frac{z'' - \beta''}{z' - \beta'} = \frac{91}{38265} + \frac{2}{91} = 0.0024 + 0.022 = 0.0244 \quad (6)$$

If, in this model, the effect of friction is neglected ($p = R_{fr}/(mg) = 0$), then the comparative uncertainty ε_2 due to the finiteness of the physical–mathematical model becomes

$$\varepsilon_2 = \frac{91}{38265} + \frac{1}{91} = 0.0024 + 0.011 = 0.0134 \quad (7)$$

Thus, the comparative uncertainty decreases by 0.011. At the same time, it is well known that neglecting friction generally increases the discrepancy between the mathematical model and the real motion of the pendulum. Moreover, this increase is not constant but depends on the values of the dimensionless parameters a and p. The modeling uncertainty becomes smaller only when p is sufficiently small and the value of a is far from resonance regions.

The apparent contradiction is explained by the fact that, when friction is ignored, the mathematical model describes the material object less accurately. Consequently, to obtain reliable experimental data and to verify the adequacy of the chosen model, a higher accuracy of the measuring instruments is required. In this case, the dimensionless experimental uncertainty $\varepsilon_{\exp}$ (the estimated comparative uncertainty in determining the dimensionless amplitude $x_{\max}$) must be reduced, so that the ratio $\varepsilon_{\exp}/\varepsilon_{\text{opt}}$ approaches unity (see Section IV). If the spread of experimental data relative to the results of computer simulation remains within the limits accepted by the researcher, the selected mathematical model may be regarded as adequately describing the observed process.

Thus, Chapter 2 completes the outline of the general informational picture: *GoP + FIQ + μ form the fundamental structure of distinguishability*, while formulas (1) - (4) establish the quantitative ultimate framework for any physical model. All subsequent development—analysis of fundamental constants, construction of new models, assessment of accuracy—rests on these limiting relations as the foundational informational law.

3. Experimental Confirmation of Gödelian Information Completeness in Measuring Fundamental Physical Constants

3.1. The CODATA Methodology and Its Limitations in the Context of Gödelian Incompleteness

The adoption of the revised International System of Units [88] [89], spearheaded by the Committee on Data for Science and Technology (CODATA), marks one of the major scientific achievements of the early 21st century. This update to the SI became possible thanks to two key factors: first, the development of unique experimental setups and novel methods for measuring physical constants; second, significant refinements in the statistical procedures used to combine decades of measurement results obtained by independent research centers worldwide.

Experimental data for physical constants are processed according to the CODATA procedure, which employs Bayesian linear regression combined with the method of least squares [14]. However, this procedure does not always yield fully adequate results [90]. The least squares method is applied to assess the consistency of results; to this end, original experimental values undergo "adjustment." In cases of conflicting outcomes, the associated uncertainties are artificially inflated within the CODATA analysis [91]. Moreover, there remains the possibility that a biased statistical expert may be influenced by personal beliefs or preferences [92]. This indicates that the methodology inevitably incorporates an element of subjective judgment [93].

Connection to Gödel's Theorems. This situation reveals a profound parallel with Gödel's revolutionary incompleteness theorems [17] [94], which fundamentally altered our understanding of the capabilities of formal systems. Just as any sufficiently rich formal system cannot prove all truths about itself, the CODATA methodology—despite its mathematical rigor—cannot eliminate the fundamental uncertainty that arises from the very act of choosing a model. The adjustment of experimental data and the inflation of uncertainties to achieve consistency amount to a de facto acknowledgment of a Gödelian type of limitation: the system cannot justify its own consistency using only its internal means.

The CODATA methodology for determining the value of a physical constant involves a specific adjustment of measurement results collected by various independent research centers over decades. This adjustment helps identify possible systematic effects that can be explicitly recognized. Nevertheless, whenever possible, the analysis of measurement uncertainty should remain free from any subjective probability or degree of belief [95]. In other words, the scope of the CODATA methodology is confined solely to the results of performed experiments and completely overlooks the systematic effect represented by the comparative uncertainty—an uncertainty dictated by the choice of the class of phenomena (GoP) and the number of variables considered in the model.

Gödelian Interpretation of CODATA Limitations. The inability of the CODATA methodology to account for the a priori uncertainty of a model is not a shortcoming of the method but a reflection of a fundamental Gödelian principle: no reconciliation procedure based on the analysis of already obtained experimental data can eliminate the uncertainty inherent in the very formulation of the model. This represents a physical analogue of the impossibility of proving the consistency of a formal system using the means of that system itself. Consequently, for such cases, the use of the finite information quantities method is warranted, as it does not rely on tools for checking consistency, asymptotic normality, weighted estimates, or correlation coefficients.

Systematic Analysis of Physical Constant Measurements: The Manifestation of Gödelian Barriers.

In a previous study [48], a detailed analysis was presented of the results from measuring physical constants using various methods, conducted by research centers between 2000 and 2019, from the perspective of the finite information quantities method. **Table 1** contains data on the magnitude of the ratio between the experimentally achieved comparative uncertainty and the recommended optimal comparative uncertainty value, presented in ascending order.

Table 1. Summary of the ratio of experimental to optimal comparative uncertainty.

Ratio $\varepsilon_{exp}/\varepsilon_{opt}$	Physical constant	Measurement method	Group of phenomena
2.3	Boltzmann constant	DCGT[1]	LMTθI
3.6	Plank constant	AGT[2]	LMTθF
4.1	Hubble constant	CMB[3]	LMTθ
7.9	Gravitational constant	Electro-mechanical methods	LMTI
15.9	Plank constant	KB[4]	LMTI
32.6	Plank constant	XRCD[5]	LMTθF
100	Gravitational constant	Mechanical methods	LMT
104	Hubble constant	BAO[6]	LMT
710	Boltzmann constant	BDL[7]	LMT

[1]DCGT—Dielectric gas thermometer; 2AGT—acoustic gas thermometer; [3]CMB—cosmic microwave background radiation; [4]KB—Kibble balance; [5]XRCD—X-ray crystal density; [6]BAO—baryon acoustic oscillations; [7]BDL—cosmic distance ladder.

Analyzing the data presented, the following patterns can be observed, revealing a profound connection to Gödel's incompleteness theorems concerning formal systems.

As one transitions from models with a small number of base quantities (LMT) to SI groups of phenomena with an increased number of base quantities (LMTθ, LMTI, LMTθF, and so on) and a corresponding growth in the number of FIQs, the ratio $\varepsilon_{exp}/\varepsilon_{opt}$ decreases. This is explained by the ability to account for a greater number of potential interactions between the increased variables considered by the researcher. In terms of Gödelian incompleteness, models within the LMT group of phenomena reside in a zone of "insufficient completeness"—they are too simple to adequately describe complex physical phenomena, leading to a dramatic increase in uncertainty. The $\varepsilon_{exp}/\varepsilon_{opt}$ ratio reaching values of 100 - 710 for mechanical methods indicates that these models lie far beyond the "Gödelian optimum."

The data in **Table 2** lead to the conclusion that the use of the BDL and BAO methods for measuring Boltzmann's constant, the Hubble constant, and mechanical methods for the gravitational constant respectively is unpromising. This represents a physical manifestation of the Gödelian principle: the formal system (in this case, the physical model with the LMT group of phenomena) proves insufficiently rich to adequately represent the phenomenon under study. No refinement of experimental technique can overcome this fundamental limitation, as it is embedded in the very structure of the chosen class of phenomena.

It must be noted that specifying the precise number of variables considered is not standard practice in scientific publications and is ignored in most studies. Therefore, to advance the applicability of the proposed finite information quantities method and the use of the optimal comparative uncertainty for testing the most accurate method of measuring a physical constant, it is necessary to reframe the concept of "comparative uncertainty" in terms that are comprehensible to all scientists and widely used in science and engineering, such as relative uncertainty.

3.2. Relative Uncertainty as a Practical Criterion for Gödel Restrictions

The cited study [48] presented a step-by-step procedure for calculating the relative uncertainty corresponding to the optimal comparative uncertainty, and the minimum relative uncertainty achieved in measuring a specific physical constant by research laboratories and centers using various methods, as published in sixty-five scientific articles. The comparison results are summarized in **Table 2**.

Gödelian Zones of Measurement Accuracy. The analysis of data in **Table 2** reveals several clear trends demonstrating the manifestation of Gödelian limitations in physical measurements.

First, the ratio r_{exp}/r_{GoP} undergoes a sharp increase when using classes of phenomena with a small number of base quantities and a small number of finite information quantities (LMTF, LMT). This corresponds to the "zone of insufficient completeness" in our proposed three-zone classification of models. Just as a formal system that is too impoverished cannot express sufficiently complex truths, a model with an insufficient number of base quantities cannot adequately describe the physical phenomenon under study.

Second, all values of the r_{exp}/r_{GoP} ratio exceed unity, confirming an important thesis of the proposed method [48]: the accuracy limit of any model is determined by the optimal comparative uncertainty (and, correspondingly, by the theoretical relative uncertainty of the group of phenomena) and is fundamentally unattainable. This represents a direct physical analogy with Gödel's incompleteness theorem: just as a formal system cannot prove all true statements within its domain, a physical model cannot achieve arbitrary accuracy, being constrained by its informational structure.

Table 2. Summary data on the ratio of experimental to optimal comparative uncertainty.

Ratio r_{exp}/r_{GoP}	Physical constant	Measurement method	Group of phenomena
1.1	Boltzmann constant	DBT[1]	LMTθF
1.9	Boltzmann constant	JNT[2]	LMTθI
1.9	Gravitational constant	Electro-mechanical methods	LMTI
2.4	Hubble constant	CMB	LMTθ
2.6	Plank constant	AGT	LMTθF
2.9	Plank constant	KB	LMTI
9.1	Plank constant	XRCD	LMTF
12.7	Gravitational constant	Mechanical methods	LMT
44	Boltzmann constant	BDL	LMT
56	Hubble constant	BAO	LMT

[1]DBT—Doppler expansion thermometer; [2]JNT—thermometer based on Johnson noise.

Take the measurement of Boltzmann's constant. Consider how we measure Boltzmann's constant. If you put the DBT and JNT methods side by side, the JNT route gets you closer to the true value. How? By fine-tuning the setup and bringing more of the influencing factors into the picture. Think of it in Gödelian terms: you're essentially building a more expressive formal system—one that can capture finer relationships in the phenomenon. But don't be fooled; this richer system still hits a wall. It can't describe everything. The inherent incompleteness remains. Yet even this expanded framework cannot escape fundamental constraints; it remains incomplete.

Fourth, electromechanical methods for measuring the gravitational constant strongly suggest that higher measurement accuracy can be achieved with considerable confidence. From a Gödelian perspective: electromechanical methods operate within the LMTI class of phenomena, which is informationally richer than the LMT class used in mechanical methods, thereby approaching the "optimal zone" between insufficient completeness and computational infeasibility.

Finally, of the three methods used to measure Planck's constant (AGT, KB, XRCD), the finite information quantities framework identifies the AGT method as the most promising route to higher accuracy in determining the constant's value. The ratio $r_{\text{exp}}/r_{\text{GoP}} = 2.6$ for AGT indicates its closeness to the theoretical accuracy limit for the LMTθF class of phenomena, signaling an approach toward the "Gödelian optimum"—the point of balance between a model's informational completeness and its practical realizability.

3.3. The Fundamental Nature of Information-Gödel Constraints

The presented analysis reveals that discrepancies between different methods for measuring physical constants do not stem from experimental carelessness or flaws in statistical data processing. These discrepancies instead reflect the fundamental Gödelian incompleteness inherent in the very models upon which the measurement methods are built. Choosing a class of phenomena with an insufficient number of base quantities imposes insurmountable limits on achievable accuracy—much like choosing a formal system that isn't rich enough makes it impossible to prove certain true statements.

In this context, Gödel's revolutionary incompleteness theorems [17] [94]—which fundamentally reshaped our understanding of formal systems—gain a new, physical embodiment. They demonstrate that limits on our ability to know the world are imposed not by external factors (like imperfect instruments or limited computing power), but by the internal structure of the cognitive process itself: by the choice of our conceptual framework (the system of units) and the level of detail in our description (the number of variables we account for).

4. Philosophical and Methodological Implications: Rethinking the Limits of Scientific Knowledge

The results considered above call for a rethink of both the nature of physical laws and the very limits of scientific knowledge. At the heart of the discussion lies the question of the ***ontological status*** of the revealed limitations: do they pertain to fundamental properties of reality, or are they a consequence of the structure of human cognition? Historically, the positivist tradition, from Comte to the logical empiricists [96] [97], proceeded from the idea of science monotonically approaching objective truth. In this picture, every improvement in experimental apparatus and theoretical tools was understood as a step toward a more accurate, ultimately perfectly correct description of the world. Uncertainty was interpreted as a temporary difficulty, bound to vanish with scientific progress.

Yet the analysis carried out within the informational-Gödelian framework points to a different kind of limitation. The comparative uncertainty arising from the finite number of variables in any model is not a temporary impediment and cannot be eliminated by technological progress. It is a ***structural property*** of the modeling process itself—analogous to how Gödelian incompleteness expresses a structural property of sufficiently rich formal systems. This line of thought compels a different view of scientific limitations and, thereby, of the philosophy of science as such.

Popper's idea of knowledge growth through bold conjectures and refutations [98], Kuhn's conception of paradigm shifts [99], and Feyerabend's methodological anarchism [100] have long been seen as competing explanations for the dynamics of science. In the light of the informational analysis, they can be reconciled. On one hand, incompleteness manifests as a limitation built into the very principle of modeling. On the other, this limitation defines the frame within which conceptual schemes shift—as described by Kuhn—and the necessity for constant hypothesis generation, as emphasized by Popper. A new understanding emerges: limitations do not merely hinder progress; they ***structure the space of possible theories.***

The proposed thesis of ***ontological incompleteness*** proceeds from the premise that informational-Gödelian uncertainty is neither a property of an "objective" reality independent of the observer, nor purely an epistemological limitation of the subject. It is a property of the ***relation itself*** between the observer and the object of study—close in philosophical status to the principles of quantum uncertainty in Bohr's interpretation [101] [102]. This understanding brings our approach near to Wheeler's idea of a "participatory universe" [103], where the observer's action does not merely record reality but co-participates in its actualization. In this context, the choice of the system of units and the class of phenomena is precisely an act of ***constituting*** the aspect of the world under investigation. Different possible choices lead to different "windows" onto reality, and each such window possesses a fundamental incompleteness.

This conclusion necessitates an analysis of the conscious observer's role in establishing constraints. In particular, the postulate of equiprobable variable selection—a key component of our approach—might seem artificial. An experienced researcher certainly doesn't select variables at random: their choice is shaped by the culture of science, existing knowledge, and intuition. However, historical examples demonstrate that at the very start of formulating new theories, the choice of conceptual frameworks is never unambiguous. For instance, in the debate over the corpuscular and wave theories of light, Newton relied on the mechanistic worldview of his time [104], while Huygens proceeded from the analogy of wave propagation [105]. Both approaches appeared equally well-founded until a critical mass of empirical data accumulated. This example underscores that at the birth of a theory; selection is driven not by strict criteria but by deep metaphysical and heuristic considerations. This is precisely the situation the equiprobability postulate reflects.

In Laudan's terms, the distinction between conceptual and empirical problems [106] clarifies that we are dealing with the former level: the selection of descriptive categories not yet tested by experience. Here, intuition, metaphysical preferences, and the aesthetics of scientific thought play a role no less significant than direct data. The history of science provides numerous examples where philosophical assumptions implicitly guided the formation of classes of phenomena. The mechanistic tradition, traceable to Descartes [107], naturally favored three-dimensional classes of phenomena such as LMT (Length, Mass, Time). The introduction of temperature as an independent variable in the 19th century reflected the recognition of a new aspect of physical processes irreducible to particle mechanics [108]. Quantum mechanics once again dismantled traditional notions: coordinates and momenta proved insufficient for describing nature, and the complementarity principle [64] [109] [110] pointed to the necessity of multiple mutually exclusive sets of variables. These historical transformations confirm the idea that the fundamental uncertainty inherent in human choice is part of a more general principle of informational/Gödelian incompleteness.

Polanyi, with his theory of tacit knowledge [111], emphasized that our decisions—and particularly the choice of variables—are grounded in experience that cannot be fully formalized. It follows that a fundamental underdetermination is present in the core essence of scientific knowledge, and it is ineradicable. In this context, the equiprobability postulate does not imply a truly random choice; it merely formalizes a state of initial symmetry: prior to the emergence of data, no single set of variables is a priori privileged.

This perspective shifts the focus to the question of model selection. Traditional criteria—predictive accuracy, explanatory depth, simplicity—remain important but are ultimately partially subjective [112]-[114]. Even Occam's Razor, with its call for parsimony [115], leads to ambiguous conclusions: in some cases simplicity means fewer assumptions, in others it means mathematical compactness or, conversely, a richer structure that can better account for the data. The optimality criterion proposed within our framework eliminates this ambiguity.

Model M_1 is preferable to M_2 if its comparative uncertainty lies closer to the optimal value ε_{opt}, provided both remain below the threshold of computational intractability. Consequently, excessive simplicity proves just as undesirable as needless complexity: the first leads to incompleteness, the second to unrealizability. In this light, Sober's concept of balancing accuracy with complexity [116] [117] receives a quantitative foundation.

This understanding also suggests a new interpretation of scientific progress. The cumulative model, which envisions a monotonic march toward truth, gives way to a picture of movement through a *space of possible classes of phenomena*. Kuhn's idea of incommensurability [99] gains a quantitative dimension here: different paradigms employ different sets of base quantities and, therefore, possess different optimal uncertainty thresholds. Progress becomes a shift toward more informative classes of phenomena—those capable of accounting for previously neglected aspects of reality. The transition from Newtonian mechanics (LMT) to Maxwellian electrodynamics (LMTI) [118], or the integration of thermodynamics (LMTθ) [119], was not merely an accumulation of facts, but an *expansion of the very structure of understanding*.

Since each Group of Phenomena carries its own limit of computational and cognitive feasibility, the trajectory of knowledge is inherently asymptotic. Technological progress expands the accessible range of models but does not erase the fundamental constraint: there always exists an optimal level of complexity, beyond which uncertainty actually increases due to intractability. Supercomputers and machine learning [120] [121] can push this boundary further out, but they cannot remove it.

Recognizing these fundamental limits of scientific knowledge carries significant societal implications. In an era where science underpins policy decisions—from climate strategies to epidemiological measures—understanding the true nature of scientific uncertainty is paramount. The reproducibility crisis [122] [123] is exacerbated by misplaced expectations of absolute precision. The informational-Gödelian analysis provides a foundation for more transparent scientific communication, where uncertainty is framed not as a random error, but as a structural property of scientific inquiry itself. Douglas's views on the role of values in science and the ethical duty of scientists to communicate uncertainties faithfully [124] find a quantitative grounding in this approach.

At the same time, the criteria for demarcating science from pseudoscience become clearer. Popper's falsifiability [67] and Laudan's problem-oriented approach [125] are now supplemented by the requirement to explicitly state the class of phenomena and the number of variables involved. Pseudoscientific theories typically avoid such specification, thereby concealing their inherent uncertainty and preventing any quantitative assessment of their predictive power. Making the declaration of the phenomenon class mandatory strengthens methodological discipline and increases the transparency of scientific discourse.

These conclusions provide grounds for moving to practical methodological recommendations for research. First, every study must clearly state the class of phenomena it employs, since this class determines the theoretical optimal uncertainty. Second, a systematic check of how results depend on the chosen class of phenomena is essential: testing with alternative classes, such as LMT, LMTI, or LMTθ, can reveal hidden incompleteness and indicate the need to shift to a richer description. Third, the concept of absolute accuracy within a fixed class of phenomena must be abandoned: achieving precision beyond its theoretical limit requires transitioning to a more informative model structure. Fourth, interdisciplinary work should be seen not as optional, but as a necessity dictated by the very nature of complex phenomena classes.

Finally, the horizons for future research come into view. Extending the principles of informational-Gödelian uncertainty to biological [126] [127] and cognitive systems [128] may lead to the discovery of new classes of phenomena with their own structural limits. In the quantum context, the possibility opens to compare Heisenberg's uncertainty [64] with the informational–Gödelian kind, potentially revealing a common fundamental source. The link between computational complexity [129] and model structure also remains a subject for further study: perhaps the Gödelian threshold of computability for a physical model is a physical analogue of known barriers in algorithmic theory.

Thus, the concept of informational–Gödelian incompleteness shapes a new understanding of scientific inquiry—not as a process limited merely by technology, but by structure itself. Science appears not as an instrument for absolutely uncovering truth, but as a modeling system inevitably constrained by its own foundations. Acknowledging this fact does not diminish its power; on the contrary, it allows us to act with greater clarity, to choose methodological strategies more precisely, and to understand more deeply the very nature of scientific explanation.

5. Conclusions

1) The work demonstrates that a model's informational structure inherently limits its achievable accuracy. These constraints originate at the very first stage—the choice of variables used to describe a phenomenon—and cannot be overcome by technological improvements to experimental apparatus. In this sense, the limits of precision are embedded within the model's design, not its implementation.

2) A key outcome is the successful quantitative expression of this structural incompleteness in physical models. The connection to Gödelian ideas here is operational, not merely metaphorical: a model proves "incomplete" if its variable set cannot fully convey information about the process. The ratio $\varepsilon_{exp}/\varepsilon_{opt}$ provides a precise measure, cleanly separating fundamental informational constraints from technical limitations.

3) The practical analysis confirms that such estimates allow for a meaningful comparison of alternative descriptions of the same phenomenon. This enables more than just selecting the "most accurate" method; it reveals the fundamental limit of a given descriptive framework and indicates whether seeking improvements within that same framework is worthwhile.

4) This approach offers a compelling explanation for persistent discrepancies in the determination of several fundamental constants. A significant portion of these discrepancies can be linked to differences in the informational structures of the underlying models. The example of the Hubble constant (H_0) tension illustrates that the divergence stems not only from different data sets but from which parameters are treated as foundational. This reframes the understanding of such enduring measurement conflicts.

5) The method establishes accuracy limits that are independent of instrumental sensitivity. These *a priori* estimates can be invaluable during experimental design, indicating from the outset whether a chosen methodological scheme can achieve the desired precision or if a shift to a different class of phenomena is required.

For researchers considering application of the FIQ method, it is essential to clarify its limitations and domain of validity. The informational–Gödelian framework presumes theories formulated within dimensional unit systems, where physical quantities decompose into well-defined base dimensions. Several classes of theories present intrinsic challenges to this assumption.

Topological theories constitute the first category. Models grounded in topological invariants—such as Chern–Simons theory or topological quantum field theories—do not rely on conventional dimensional observables. In such cases, measurable quantities are discrete topological charges rather than continuous dimensional variables, rendering the GoP classification ill-defined.

A second limitation arises in theories with emergent dimensionality. Frameworks in which spacetime dimensions are not fundamental but emergent, including loop quantum gravity and certain string-theoretic constructions, violate the fixed-μ assumption. Here, the parameter μ ceases to be external and instead becomes a dynamical quantity whose value must be derived from deeper structural principles.

At the Planck scale, further breakdowns occur. In regimes dominated by quantum gravity, independent measurement of spatial and temporal intervals loses operational meaning. The FIQ assumption of independent informational content fails when $\Delta x \cdot \Delta t \gtrsim \ell_P^2$, with ℓ_P denoting the Planck length, undermining the separability required for dimensional classification.

Non-equilibrium and chaotic systems present a different class of difficulties. For systems lacking stable characteristic scales—such as turbulent flows or far-from-equilibrium dynamics—the identification of a meaningful range S becomes ambiguous. Although the framework remains conceptually applicable, practical implementation demands advanced methods for dynamic scale identification.

Biological and chemical systems introduce additional, domain-specific constraints. Their intrinsic multi-scale nature spans spatial ranges from angstroms to meters and temporal ranges from femtoseconds to years. When phenomena inherently couple such disparate scales, the definition of a unique GoP becomes ambiguous.

Moreover, many biologically relevant observables—such as fitness, enzymatic efficiency, or metabolic rate—are emergent, composite quantities that resist clean reduction to fundamental dimensions. In such cases, the $z' - \beta'$ decomposition may fail to capture functional meaning in a unique or invariant manner. This difficulty is compounded by the stochastic and discrete character of many biochemical processes: reaction networks and gene regulatory circuits often involve small molecular copy numbers, invalidating continuum FIQ approximations based on $\mathbb{R}$-valued variables.

Living systems further operate in non-equilibrium steady states characterized by continuous energy dissipation. The equilibrium-oriented dimensional assumptions underlying GoP classification may therefore inadequately describe dissipative biological structures. Finally, biochemical interactions are strongly context-dependent: the same variable, such as enzyme concentration, may encode different functional information depending on cellular state, violating the assumption of fixed informational content per variable.

Despite these limitations, the central insight of the framework remains intact: model complexity reflects fundamental trade-offs between descriptive completeness and computational tractability. Each identified limitation points not to failure but to potential extensions—such as generalized informational measures beyond dimensional analysis for topological theories, or stochastic variants of FIQ adapted to discrete biological systems.

We anticipate that the wider application of this approach will enhance the analysis of physical models and elucidate a range of inconsistencies accumulated in precision metrology. While not claiming to be a universal solution, it provides a practical tool for both metrology and any field requiring a rigorous assessment of the descriptive limits inherent in a model.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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