

Hypothesis

Entropy, the Paradoxical Predicate of Order, Mind, and the Intellectual Beauty of Discovered Truth

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Abstract

We present a unifying thesis which posits that the biological resolution of uncertainty is a fundamental adaptation to entropy's negative impact on the highly ordered molecular structures required to maintain the living state. These molecular biological adaptations are highly conserved and play a critical role in the survival of the earliest multicellular organisms and the vertebrates thereafter. The imperative to reduce cognitive uncertainty is effected through the dopaminergic Medial Forebrain Bundle (MFB) Reward Prediction Error (RPE) mechanism, or its homologous equivalents, to compute a biological valuation of information. This hypothesis is supported by the central role of the MFB seeking system as the neural substrate of exploratory behavior that leads to the reduction of uncertainty when information is apprehended and cognitively assimilated. We define the human experience of intellectual beauty as the subjective emotional reward that is activated by the MFB seeking system. Accordingly, humans experience intellectual beauty when a high-entropy state of confusion is suddenly resolved into a low-entropy state of insight. In humans, the neuroanatomical substrates of inductive reasoning, inquiry, and the intellectual beauty to which they lead are present at birth. What develops postnatally is synaptic plasticity in the connections among these neurons that is activated in the loving didactic relationship that is established between mother and child during infancy. This dynamic is critically dependent on observational learning on the part of the child. It is supported by the joyful engagement and emotional support of the mother. This provides a paradigm of joy in learning that we propose is the developmental origin of intellectual beauty. This is the reinforcement that maintains inquiring behavior in the search for information that is needed to resist the adverse effects of entropy on life. This paper traces the continuous thread of uncertainty resolution from its phylogenetic origins in associative learning to the intuitive science of early childhood, and ultimately to the highest levels of human inquiry in science, as well as literary, musical and visual arts. The intuitive scientific method gives rise to the collective intelligence of groups, an evolved trait that likely contributed to the success of our hominin ancestors. At the societal level, this collective intelligence scales into the institutional working of markets, driving the macroeconomic price discovery of new information to counter entropy. Importantly, we compare the cost of information across the disparate domains of pharmaceutical drug discovery and the contemporary art market to demonstrate that the imperative to reduce uncertainty manifests as a universal, falsifiable mechanism for the "price discovery" of information.



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1. Entropy and Information: The Physical Predication of Intellectual Beauty

The statistical mechanical understanding of entropy explains that it is a measure of disorder toward which all systems, including the entire universe, tend as space–time evolves (See Ingo Muller’s history of thermodynamics [1] in which he provides Boltzmann’s derivation of formula for the entropy of a volume of gas in terms of disorder, $S = k(\ln W)$, where S = entropy, W is the number of different potential microstates of the gas, and k is Boltzmann’s constant (1.38×10^{-23} J/K). A microstate is characterized by the position and momentum of each of the molecules of a gas. Accordingly, W is treated on a statistical basis of the velocity distribution of gas molecules.). The total entropy of the universe is always increasing [2]. This raises important questions concerning the origin of the complex order that is a defining characteristic of the molecular machinery of life, and human consciousness. Entropy is not only the source of disorder in the universe but also the physical predicate of the creative agency responsible for the order that is an essential property of life and mind. The inherent paradox of the premise of entropy as a predicate of order is itself a baffling manifestation of perceived entropy. The history of science has consistently demonstrated that paradox provides fertile ground for curiosity, exploration and the inquiring behaviors that lead to insight and the discovery of truth. The nature of entropy, curiosity, inquiry and the discovery of truth to which it leads has been studied within the disparate disciplines of physics, neuroscience, psychology, epistemology, and esthetics. We believe that a synthesis of this vast scope of perspectives can be accomplished by building our argument from first principles. Given its pervasive manifestation in events at all scales from the subatomic to the cosmological, it is essential to begin with entropy, and the related phenomenon of information.

The resolution of the paradox of entropy as a predicate of order lies in the fact that entropy is not only the inexorable unfolding of disorder in the universe but also the phenomenon that allowed the force of gravity to initiate the formation of stars. The universe began approximately 13.8 billion years ago when space–time and all the matter and energy that will ever exist came into being in the highly condensed form of a singularity called the Big Bang. Relative to subsequent times, the entropy of the nascent universe was at its lowest value [3,4] and has been increasing ever since. The rapid expansion of space functioned as the crucial catalyst for the future generation of complexity (order) by physically stretching the primordial probability distributions of elementary quanta to create a structural “canvas” across the cosmos. Thereafter, it is on this “canvas” that the laws of physics exerted their influence to create order from chaos. The universe cooled sufficiently within a few hundred thousand years that protons and electrons could form stable hydrogen atoms. Gravitational attraction within denser regions of matter condensed hydrogen sufficiently to ignite nuclear fusion reactions in the cores of newly formed stars. The key point here is that the positional entropy, or disorder, in the distribution of hydrogen atoms that resulted from the cosmic expansion of space allowed the force of gravity to exert a creative agency in star formation, the essential first step in the origin of life and mind. (To be physically precise regarding the physics of this *canvas*, the rapid expansion of space vastly increased the physical volume of the universe, which lifted the ceiling of maximum possible entropy ($S_{\max}$) far faster than particles could physically rearrange themselves to fill it. This created an entropy gap ($\Delta S = S_{\max} - S_{\text{uni}}$) [5]. It is important to note that

while a uniform distribution of gas represents maximum thermal entropy, it represents extremely low gravitational entropy [3,5]; gravity increases entropy by clumping matter together. In thermodynamics, this gap is a direct measure of available free energy, defined by the equation $\Delta F = T\Delta S$ (where ΔF is free energy and T is temperature). Because any irreversible process that performs physical work inevitably creates entropy, this free energy is the only energy capable of driving the processes required to build complexity. Within the early superheated primordial plasma, intense radiation pressure initially prevented ordinary baryonic matter from utilizing this free energy to clump together. However, cold dark matter—which is immune to this radiation pressure and therefore invisible—began to collapse under the influence of gravity. This amplified primordial density fluctuations to form an invisible scaffolding of dense dark matter ‘halos’—regions that would appear as completely empty space to light, but which act as massive gravitational wells. As a result of continued cosmic expansion, the universe eventually cooled sufficiently within a few hundred thousand years that protons and electrons could form stable hydrogen atoms, effectively decoupling matter from light. Released from the radiation pressure, this newly stable hydrogen gas was free to fall into the gravitational wells of these pre-existing dark matter halos. It was within these dark matter ‘seeds’ that gravity utilized the available free energy to compress hydrogen sufficiently to ignite nuclear fusion reactions in the cores of newly formed stars.

To this point, in his seminal book, “What is Life” [6], Erwin Schrödinger postulated that to avoid the rapid decay to the maximum entropy state of thermodynamic equilibrium known as death, living organisms recognize, approach and assimilate order as the antidote to the life-destroying effects of entropy. As pointed out by Roger Penrose [7], the Sun is the local source of order in the solar system because the radiant energy of the Sun that hits the Earth derives from a single source in the sky. These photons have shorter wave-lengths (higher frequency) and are therefore more energetic than the photons in the cosmic background radiation. This allows the energy of the high-frequency photons that emanate from the Sun to be efficiently captured by photosynthetic processes in plants via the energy transfer that is utilized to create complex carbohydrate molecules. The carbohydrate molecules contain more order than the carbon dioxide and water molecules from which they are synthesized. The information inherent in the point-source origin of high-energy photons of sunlight is captured in the highly ordered structure of complex carbohydrate molecules via the agency of photosynthetic energy transformations of the plant’s metabolism. It is this order that is retained in the biosphere of the Earth, while the amount of energy absorbed from incident high-energy photons of sunlight is radiated back to space in a greater number of low-energy photons. Order or information is the essential thing that is captured and retained by the biosphere. Prigogine makes a similar point in his book [8], in which he argues that organisms and ecosystems consume “high-energy, low-entropy photons”. This energy is to perform the biological work needed to maintain the living state far removed from equilibrium. He defines life far removed from equilibrium as a dissipative structure that radiates “low-energy, high-entropy” photons back into the surrounding environment, and ultimately to space.

From the perspective of Darwinian biology, all selective pressures must be viewed as agents of entropy. Therein lies the high survival value of information in the struggle for survival. This follows from the relationship between entropy and information that is suggested by the similarity of their mathematical expressions, as explained in Figure 1 below.

As the physical entropy of a system increases, the amount of information needed to describe its state increases accordingly. The game of pool is often used to illustrate how this dynamic unfolds over time. At the beginning of the game, the pool balls are arranged near one end of the table in a tight, highly ordered V-shaped formation. When

struck by the cue ball, the pool balls scatter into an increasingly disordered formation. Historically, thermodynamic entropy (the Boltzmann/Gibbs measure of physical disorder) and Shannon–Weaver entropy (the measure of informational uncertainty) were considered distinct physical concepts. However, not only do they share a fundamental mathematical form, but they are also conceptually equivalent. The Shannon–Weaver formulation, calculated in dimensionless bits, quantifies the exact amount of missing information an observer would need to completely specify the precise, disordered spatial coordinates of the pool balls at any given moment. Consequently, the system’s thermodynamic entropy represents a theoretical information deficit; it is the exact measure of the information an observer lacks in order to calculate the precise reversal of the system’s vector trajectories back to its initial, low-entropy state.

Boltzmann Entropy (Statistical Mechanics) $S = k_B \ln W$ Where W represents the number of equally probable microstates (molecular disorder), and k_B is Boltzmann’s constant, measured in Joules per Kelvin (J/K).
Gibbs Entropy (Variable Probability) $S = -k_B \sum p_i \ln(p_i)$ Where p_i is the probability of a particular microstate occurring. This generalizes Boltzmann’s formula for systems where microstates do not have equal probability.
Shannon–Weaver Entropy (Information Theory) $H = -\sum p_i \log_2(p_i)$ Where H represents informational uncertainty (typically measured in bits), and p_i is probability of occurrence of a specific event or message.

Figure 1. The equations $S = k_B \ln W$ and $S = -k_B \sum p_i \ln(p_i)$ represent Boltzmann’s and Gibbs’ formulations, respectively, of the exact same underlying entropic quantity. As later demonstrated by Claude Shannon, the Gibbs equation shares fundamental mathematical form with the formula for the Shannon–Weaver Entropy (uncertainty) (see this text for further explanation).

The living state is a highly ordered system far removed from equilibrium that is constantly being degraded by entropy. Biological work must be done to overcome these effects, and for this reason, all forms of life seek, recognize, and assimilate information in the effort to maintain metabolic, cognitive, and behavioral homeostasis. Perhaps the most compelling example is phototropism, in which plants orient their leaves to the Sun to maximize the capture of high-energy photons, or how the honeybee uses a “Waggle Dance” to communicate to other worker bees the direction of a food source relative to the Sun’s azimuth [9]. Just as these simpler organisms biologically harvest low-entropy energy and spatial information to resist physical decay, animal nervous systems evolved to recognize and assimilate information inherent in spatiotemporal correlations among stimuli to reduce cognitive uncertainty. Of course, the cognitive resolution of informational uncertainty does not resist entropy in the same manner as the expenditure of ATP in the performance of metabolic work. Rather, it operates as a vital evolutionary extension of that same survival imperative. Because resolving ambiguity serves as a high-level cognitive adaptation for reducing entropy within the brain’s predictive models, the apprehension and cognitive assimilation of information provides a profound evolutionary reward. By proactively predicting and resolving environmental ambiguity, the brain minimizes the risk of fatal surprises, thereby maintaining biological homeostasis. It is this biological

reward of uncertainty reduction that humans consciously experience as the pleasure of intellectual beauty.

2. Curiosity, Inquiry and the Search for Meaning

The search for meaning has its origin in the human desire to understand reality in all its manifestations. Aristotle wrote that “All men by nature have a desire to know” [10]. This quest necessarily puts the inquirer in direct contact with the unknown and the emotional and behavioral responses to it. Curiosity is the cognitive state that leads to exploration and procedures of inquiry that culminate in a moment of insight. This is when confusion yields to clarity in the form of a conjecture that has the potential to explain what was incomprehensible before. The phenomenon of insight has been the subject of intense philosophical analysis, as well as psychology and neuroscience research [11]. As pointed out by Jirout [12], curiosity initiates exploratory behavior and is a vital factor in successful learning:

Young children’s learning is driven by exploration to make sense of the world around them. . . *This exploration can result from curiosity.* . . and lead to active engagement in learning. . . . *The active choice of what to learn, driven by curiosity can provide motivation and meaning to information and instill a lasting positive approach to learning in formal educational contexts.* [Emphasis added]

In the absence of any component of self-directed learning, formal educational environments governed by highly structured curricula and teaching methods can have an adverse effect on student progress because they often do not support curiosity and the evolved procedures of intuitive inquiry that follow naturally from it (see below). Repeated failure to make progress leaves students in a perpetual state of uncertainty, frustration, and anxiety that often causes aversion to traditional learning environments and methods. Tragically, under these circumstances some students may be inclined to the conclusion that they lack sufficient intelligence to succeed in academic activities. While it is fair to say with Aristotle that all humans have a desire to know, we also must acknowledge that all children do not exhibit the same degree of curiosity and success in learning. Curiosity and confidence in learning can be stultified by many environmental causes, including parental neglect or the malign influence of other people encountered during early childhood, as well as the possibility of encountering ineffective teachers in the earliest stages of education outside the home. Alternatively, nurturing the experience of intellectual beauty and the pleasure it generates reinforces curiosity, and maintains inquiring behavior and the knowledge to which it leads.

3. Esthetics and Intellectual Beauty

The intimate connection between the esthetic experience and its cognitive substrate was described by Medieval philosopher and theologian Thomas Aquinas [13]. In his in-depth masterwork on beauty in the arts, titled “Beauty & Imitation”, Daniel McInerney [14] elaborates on the mimetic nature of re-presentational art and the emotional, cognitive, and epistemic nature of the viewer’s response to it:

The delight we experience in works of mimetic art is what we might call mimetic delight. It is a peculiarly cognitive delight. A delight in knowing.

California Poet Laureate, Dana Gioia [15], captured this epistemic aspect of the esthetic experience likewise: “Beauty makes us delight in the very act of knowing”. Expanding on this idea, Gioia continues:

Perceiving Beauty we have the sense of seeing something perfect in its own way. A perfection apparent not only on the surface, but a quality we sense in the very heart of the thing. . . . Beauty is a true and powerful way of looking

into the nature of reality. . . The order of the universe, from the microcosm of the atom to the macrocosm of the galaxy, is interconnected. . . As products of nature or evolution, we have been formed to respond to its structure. . . Beauty is not something we manufacture, it is something we discover and recognize. . . The experience of Beauty is our recognition of the deepest tendencies of the forms of the universe, our highest and most complete integrative level of understanding. [Emphasis added]

Gioia alludes to the beauty perceived in the oneness of all aspects of reality at every scale. He posits that beauty, per se, is embodied in the “very heart of a thing” and defines its essence. Going further, we propose that beauty is experienced when the inquiring human mind discovers meaning in the essence that is revealed, understood and known as the truth about an object of inquiry. It is for this reason that Gioia, and McInerney using similar language, states that the experience of beauty leads to a delight in knowing. In this paper, we also call attention to the converse, namely that seeking truth through scholarship leads to the experience of a form of beauty that evolutionary psychologist, Randy Thornhill, calls intellectual beauty. Thornhill defines intellectual beauty not in reference to the final result of successful inquiry, the ultimate truth that is discovered as the essence of a thing, but to the process of inquiry that leads to it [16]:

Intellectual beauty is the beauty that scholars in all academic disciplines find in scholarship. Intellectual beauty is the most noble goal of academic pursuit, and is a sublime reward of the pursuit.

Surely there is the arresting beauty that is perceived in truth as the revealed essence of an object of inquiry, but Thornhill points to the beauty that is experienced in scholarship and academic pursuit, that is, during inquiry itself. This is an important distinction. To experience intellectual beauty in the pursuit of understanding is indeed a sublime reward of human inquiry because it anticipates the beauty of truth not yet fully revealed. We will show why this idea goes not only to the heart of epistemology and aesthetics but also evolutionary psychology in consideration of the question: What beauty is experienced during inquiry as it progresses toward the moment when confusion yields to clarity? Humans have evolved to appreciate intellectual beauty in wonder. Curiosity focuses attention on what is not understood in a way that leads naturally to evolved intuitive procedures of inquiry and ultimately to putative understanding in a moment of insight (see Dewey below). This is the moment when one is surprised by a sudden and sometimes unexpected transition from confusion to clarity in the form of a novel hypothesis about an object of interest, or the inspiration for a beautiful artistic or literary creation. If confirmed, the hypothesis reveals a new understanding about the object of inquiring behavior. Intellectual beauty therefore culminates in the ultimate beauty that is experienced when a verified explanation of a phenomenon or the inspiration for a work of art is attained.

Science and mathematics, on the one hand, and various forms of art, on the other, are often viewed as representing diametrically opposed domains on the continuum of human intellectual and creative activity. Nevertheless, the inclusion of artistic and literary expression with science and mathematics as forms of understanding is warranted in light of what Bertrand Russell [17] wrote about the consilience that is achieved in the beauty that they share:

Mathematics, rightly viewed, possesses not only truth, but supreme beauty—a beauty cold and austere . . . yet sublimely pure, and capable of a stern perfection such as only the greatest art can show.

Russell’s comparison of mathematical beauty to the beauty of art has been vindicated by brain fMRI studies performed in the burgeoning field of neuroaesthetics that showed that

the experience of mathematical beauty correlates with activity in the medial orbito-frontal cortex, the same part of the emotional brain that is activated by the experience of artistic forms of beauty [18]. In the quote above, Russell points to an intimate connection between beauty and truth, not only in art but also in mathematical inquiry and discovery. In so doing, he raises beauty beyond its esthetic significance to an epistemic one as an important criterion in the determination of truth. The elegance and simplicity of a mathematical proof, for example, lends credence to its method and confidence in its conclusion, while a complicated, tortuous proof often leads to suspicion of its veracity and further scrutiny. So, the notion that beauty and elegance are criteria of truth, or at least qualities that are consistent with it, is familiar to mathematicians and scientists. In the furtherance of Russell's thesis, we explore the abstraction of essence in mathematical and scientific inquiry, and the abstraction of form in visual and literary art to demonstrate common epistemological, esthetic, and cognitive features across the whole spectrum of human intellectual and creative activity. Throughout this paper, we rely on neurobiological data to provide the empirical evidence to support our suppositions while using historical examples from art and science as conceptual illustrations of the mechanism in action.

4. The Role of Sudden Insight in Inquiry

Consideration of two profound examples presented by Hadamard [19], one from art, another from science, will help to illustrate this function of intellectual beauty. In these two examples of sudden insight, we are concerned not with the conscious processes of deductive reasoning, but with inductive reasoning that is mediated by the cognitive unconscious mind [20]. Hadamard quotes Mozart's description of his own creative process:

... thoughts crowd into my mind as easily as you could wish. Whence and how do they come? I do not know and I have nothing to do with it. Those which please me, I keep in my head and hum them. . . Once I have my theme, another melody comes, linking itself to the first one in accordance with the needs of the composition as a whole: the counter-point, the part of each instrument, and all these melodic fragments at last produce the entire work. Then my soul is on fire with inspiration. . . until I have the entire composition finished in my head. . . then my mind seizes it as a glance of my eye a beautiful picture. . . it does not come to me successively. . . , but it is in its entirety that my imagination lets me hear it [19]. [Emphasis added]

The apparently effortless aspect of Mozart's creative process is noteworthy in this account. Even more striking is the fact that Mozart's creative process led him to a height of rapture and transcendence of time in which he experienced his composition not as a sequence of sounds but simultaneously as a "picture" in a "glance of eye".

A second example from the field of scientific inquiry provides a striking illustration of sudden insight. The discovery of the chemical ring structure of the benzene molecule by the famous nineteenth century theoretical chemist August Kekulé offers an example of the inquirer's observation of his own musings during what seems to have been a hypnogogic mental state that led to his moment of insight. The following is a translation of Kekulé's original German account [21]:

There I sat, writing on my textbook; but it was not going right; my mind was on other things. I turned the chair to face the fireplace and slipped into a languorous state. Again, atoms fluttered before my eyes. Smaller groups stayed mostly in the background this time. My mind's eye, sharpened by repeated visions of this sort, now distinguished larger figures in manifold shapes. Long rows, frequently linked more densely; everything in motion, winding and turning like snakes.

And lo, what was that? One of the snakes grabbed its own tail and the image whirled mockingly before my eyes. I came to my senses as though struck by lightning; this time, too, I spent the rest of the night working out the results of my hypothesis.

In this example, it is clear that Kekulé's unconscious mind accomplished what Freud originally described [22]. It presented his conscious mind with a representation of hypnagogic cognitive processes in the form of symbolic imagery. (It is known that hypnagogic mental cognitions include a process called *autosymbolism*, in which abstract ideas or concepts can be represented as vivid imagery. The imagery may be perceived by the hypnagogic as a pictographic metaphor of more abstract ideas [23]. Moreover, unconscious mental activity can influence the conscious mind even during a state of full wakefulness, as Freud demonstrated so thoroughly in his analyses of slips of the tongue and wit [22]. The meaning was not lost on Kekulé, who was aroused from his mental wanderings "as though struck by lightning". The pictographic and linguistic symbolism of dreams was interpreted by Freud as a disguised manifestation of material that the superego would view as shameful or forbidden. In the psychoanalytic tradition, the symbolic transformation of inconvenient, embarrassing, and repressed material is understood as an attempt by the unconscious mind to transform an irreconcilable conflict between the Id and the Superego into a form more acceptable to the censure of the Ego's defense mechanisms [24], and thus more available to conscious awareness and resolution. This suggests that the same unconscious cognitive mechanisms that Freud understood from the psychoanalytic perspective have utility in solving problems of a more general nature. The key insight required for Kekulé to solve the unknown conformation of the benzene molecule was to consider the possibility that a closed cyclic arrangement of the carbon atoms, rather than an open structure, is the essential defining characteristic. Once this idea was visualized as a hypnagogic metaphor in the form of a snake circling back to grasp its own tail, the degrees of freedom for tetravalent carbon bonds were more limited and easier to realize [25]. Neuroimaging studies have shown that solution of a semantic problem such as an anagram by spontaneous insight, as opposed to a process of deductive reasoning, is associated with increased functional MRI activity in the right anterior temporal lobe [26]. Moreover, a sudden burst of high-frequency EEG activity was noted in the same area about 300 msec. before the subjects indicated that they had reached a solution by insight. These effects were not observed for non-insight anagram solutions derived through deductive reasoning.

5. Inquiry Is an Evolved Response to Uncertainty and Its Progress Is Incremental and Tortuous

In "Useful Procedures of Inquiry" [27], philosopher Rollo Handy and co-author E.C. Harwood describe how successful inquiry progresses incrementally and tortuously from confusion to putative understanding:

In the course of inquiry, as the inquirer initially observes and measures he may note connections among the things measured and imagines other possible connections . . . Partial tentative descriptions are developed from initial observations. The inquirer, *temporarily baffled* in his effort to achieve useful adequate description, imagines various possibilities or notions among which he selects the seemingly more promising as the guide to further observation. If lucky or skillful or both, his additional observations develop further the original tentative descriptions. If not adequate for the problem confronted by the inquirer, he again is baffled and develops notions or imagines other possible connections among things, from which he chooses a guide for further observations and so on, until *satisfactory description* is achieved. [Emphasis added]

The course of inquiry begins with an observation of a phenomenon that is not understood. Then, through curation of repeated observations and measurements, the formation of a conjecture or “satisfactory description” of the phenomenon of interest is realized. The examples from Mozart and Kekulé above show that the intuitive, unconscious processes of inductive reasoning lead by inference to sudden insight that demarcates the transition from confusion to putative understanding. In this context, “understanding” manifests as a conjecture that might explain a phenomenon or resolve a problem. There is a critical gap in our knowledge of the neurobiology of inquiry, however, concerning the mechanism of inductive reasoning that leads to sudden insight. (See Becker and Cabeza’s recent work [28] below, however, for their major advance in remedying this deficiency.)

6. Kant’s Realization That the Mechanism of Inductive Reasoning Implies the Unitary Nature of Reality

The unitary nature of reality, as proposed by Kant, reiterates ancient Greek philosopher, *Parmenides*, who was persuaded that, because nothing comes from nothing, what exists eternally, is immutable, uniform and of one fundamental nature throughout. *Parmenides* and Kant anticipate physicist David Bohm’s theory [29] that everything is connected at a fundamental quantum level of reality. In reference to Kant’s conception of beauty in his “Critique of the Foundations of Taste”, Egginton [30] explains Kant’s insight that inductive reasoning implies the unitary nature of reality:

Kant now realized, whenever we connect two or more specific claims as being examples of a more general truth, of an idea that contains them both, the very coherence of our judgments requires us to assume a web of connections that links each specific instance to the whole of creation. . . [Emphasis added]

Inductive reasoning, which infers that two or more specific claims are examples of a more general truth, necessarily presumes the inherent wholeness, or unitary nature of reality. While the neuroimaging studies of Jung-Beeman et al. discussed above have demonstrated that the right anterior temporal lobe is a critical neuroanatomical element in the neural network that mediates sudden insight, it is Kant’s realization that points the way to the cognitive mechanism. The discovery of an overarching principle that explains a multiplicity of observations requires the ability to infer what is common to them all.

7. The Abstraction of Essence Is the Cognitive Mechanism of Sudden Insight

This fundamental operation of inductive reasoning is defined in mathematics by the concept of the equivalence relation, which is the property that defines a criterion for set inclusion. What is common to any number of objects or thoughts is the criterion for their inclusion in a set. As Mynard [31] explains, inclusion in the “set of all groupings of three things” is defined by the analogical cardinality of “three”, irrespective of any other property or characteristic of the diverse objects grouped together by threes. The cardinality of the number 3, that is “Threeness”, is what is common to all groups of three things. Similarly, as explained by Richards and Franklin [32]:

The concept of the letter “a” accounts for many calligraphic variations. . . but also all the variations in hand writing. Our brain “forgets” all these differences and identifies all these symbols by considering them equivalent.

From the perspective of the neurobiology of memory, it is perhaps more accurate to say that learning to ignore the distinguishing features of all forms of the letter “a” rather than literally forgetting them is what is required to understand that they all represent “a”. In either case, synaptic plasticity in the neural networks of perception and memory is

essential to the discovery of a criterion for set inclusion. This is the binding principle, the essential property or the essence, that defines them all. Synaptic plasticity is required for the abstraction of essence. Again, Richards and Franklin [23] explain the importance of this phenomenon in the context of abstracting the essence of a multiplicity of diversely colored soccer balls using the example of regression analysis in statistics:

When performing a regression in statistics, using a function with many parameters builds a model. . . that fits the old data very well. . .but that fails to predict new data. . . The mnemonic equivalent of a complex model would be to store memories for the specific patterns on every soccer ball that we have ever seen. . . In contrast, using a function with few parameters builds a model that might not perfectly describe the old data, but will be better at predicting new data. The mnemonic equivalent would be to forget most details regarding soccer balls we have seen, and instead remember that they generally are [spheres] made up of interlocking pentagons and hexagons. . . This will lead to better prediction of the appearance of new soccer balls we encounter. [Emphasis added]

The details of diverse colors and patterning of the polygons of the patchwork surfaces of soccer balls are antithetical to abstraction of soccer ball essence. The inquirer must learn to ignore the distinguishing characteristics of the many observations of a phenomenon to discover what is common to them all. Accordingly, ultrastructural changes in synaptic plasticity in the neural networks of perception and memory are required for the emergence of insight. (It is important to note that the molecular mechanisms responsible for synaptic plasticity are phylogenetically ancient, highly conserved and have been demonstrated in invertebrates, notably including in *Aplysia*. See, for example, the E. R Kandel Nobel Prize Lecture [33].) The difficulty of the problem the inquirer is attempting to understand may be related to the length of time required for the necessary modifications in dendritic spines to be accomplished. The efficacy of Bacon's and Dewey's method of scientific induction that is discussed below may derive from an ability to facilitate or guide the synaptic remodeling that is required for sudden insight.

8. Bacon's and Dewey's Method of "Scientific Induction"

Kant's philosophical predecessor, Francis Bacon, in his famous work, *Novum Organum* [34] ("Novum Organum" or "New Organon" is a reference to Aristotle's work "Organon", which was a treatise on logic and deductive reasoning. The full title of Bacon's treatise is "Novum Organum, sive Indicia Vera de Interpretatione Naturae", which translates as "New Organon or true directions for the interpretation of nature." Bacon's use of the words "true directions" is intended to emphasize that inductive reasoning makes a greater contribution to successful scientific inquiry than deductive reasoning.), on the essential role of inductive reasoning in scientific inquiry, provided a method to facilitate hypothesis formation, which the latter-day American philosopher John Dewey reiterated. Dewey took pains to note that, while the method facilitated the conscious realization of an explanatory hypothesis, no one understands the process by which the mind reaches such a vital milestone in inquiry (see below). The method consists of observation of a phenomenon of interest and systematic curation of descriptive data. Specifically, they advocated for a procedure to facilitate inductive reasoning in which as many instances as possible of a phenomenon under consideration be listed along with counter-examples and then examples of variation in the phenomenon. Bacon and Dewey proposed that, if done properly, this procedure would provide the context for the realization of a conjecture or hypothesis as a putative explanation of those data. In other words, the method of data curation provides a context that promotes the realization of the common feature, the over-arching principle that explains those data.

In his book, *How We Think*, John Dewey [35] elaborates as follows on the respective roles of inductive and deductive reasoning in inquiry:

While *induction moves from fragmentary details (or particulars) to a connected view of a situation (universal)*, deduction begins with the latter and works back again to particulars, connecting them and binding them together. *The inductive movement is toward discovery of a binding principle; the deductive toward its testing, confirming, refuting, modifying it on the basis of its capacity to interpret isolated details into a unified experience. So far as we conduct each of these processes in the light of the other, we get valid discovery or verified critical thinking.* [Emphasis added]

Concerning the mechanism of inductive reasoning, Dewey writes:

Control of the formation of suggestion is necessarily indirect, not direct; imperfect, not perfect. . . *no rules can be stated that will guarantee correct inference* [35] (p. 84). [Emphasis added]

What Dewey describes is a mechanism of inductive reasoning that has the appearance of a hidden one-step process that apparently originates in the cognitive unconscious mind. While we propose that this necessarily involves elements of synaptic plasticity, no one is aware of these modifications in one's own brain. Rather, the "awareness" manifests as the emergent phenomenon of spontaneous insight when what is common to a set of observations suddenly becomes obvious.

9. John Dewey's Experimental Chicago School

In view of the formal procedures recommended by Bacon and Dewey to facilitate what they called scientific induction, Cowles [36] notes that Dewey was surprised to observe that children use an intuitive version of the scientific method when they are playing or working on a problem. In 1896, Dewey established an experimental school in Chicago to observe students from pre-school through high school. Dewey and his colleagues found that children learned best when they worked together and spoke spontaneously to each other and with teachers to describe what they were doing. We should note that sharing information, observations and ideas during mutual learning, problem solving, or play informally accomplishes the equivalent of what Bacon and Dewey achieved with their formalized process of data curation, namely, a context that is conducive to the emergence of sudden insight. Dewey wrote in his book, *How We Think*, the following description of a "complete thought" [35] (p. 72):

Each instance reveals, more or less clearly, five logically distinct steps: (i) a felt difficulty; (ii) its location and definition; (iii) suggestion of possible solution; (iv) development by reasoning of the bearings of the suggestion; (v) further observation and experiment leading to its acceptance or rejection; that is, the conclusion of belief or disbelief. [Emphasis added]

As observed by Cowles [36], it conforms to the sequence of steps in the formal scientific method, as well as observations of children as they worked together on a problem or activity. The "suggestion of a possible solution" in step iii refers to a conjecture that emerges spontaneously from the interactions among individuals working in a group. What Dewey observed in the students of his experimental school was the spontaneous emergence of hypotheses by unconscious mechanisms of inductive reasoning, and subsequent testing of those hypotheses by manipulation of variables, observations of the effects of those manipulations and, finally, reaching conclusions using elements of deductive reasoning. Dewey and his colleagues realized that young children were using the scientific method without any formal training. How did this method, that has proven time and

again to be the most efficient way to discover truth about phenomenal aspects of reality, become such an innate, intuitive cognitive mechanism for the discovery of meaning and the understanding of reality? Cowles [36] alludes to an origin of the intuitive scientific method that is used by children in the “traits and behaviors of our human—and sometimes even non-human—ancestors”. In support of this conjecture of Cowles, we explain below that mammals and birds exhibit sequences of exploratory behavior that are functionally equivalent to the intuitive scientific method used instinctively by children as they explore to learn.

10. Intuitive Science Is Based on Ancient Neurobiological Mechanisms of Behavior

The evolved innate paradigm of the scientific method that children use to explore and understand the world has ancient phylogenetic origins in the neurobiology of instinctive behavior and the mechanisms of classical and instrumental conditioning. The ethologist Wallace Craig suggested the division of instinctive behavior into appetitive and consummatory phases that are followed by a period of relative rest [37]. During the *appetitive* or *seeking phase*, the animal explores the environment in pursuit of a desired object like food, water or a mate that is essential for individual, and ultimately, species survival. The appetitive phase by its nature involves both a desire (Ethologists refer to desire in the context of the appetitive phase of instinctive behavior as *Action-Specific Energy*, while behaviorists of the American school of psychology call it *Drive* or *Motivation*.) for what is sought and the impulse to seek it. The goal or object of seeking behavior is called the *sign stimulus* or *releaser*, because this is the stimulus that initiates the instinctive *consummatory* response. This is a stereotypical sequence of motor acts called the *fixed action pattern* or FAP [38,39]. The neural substrate of seeking behavior is the medial forebrain bundle (MFB), together with its extensive forebrain connections. The MFB comprises the axons of dopaminergic neurons that have their cell bodies in the midbrain. These neurons terminate in the nucleus accumbens, one of the deep telencephalic nuclei, and other forebrain structures. Activation of the MFB maintains appetitive or exploratory behavior through the reinforcing effects of dopamine in forebrain sites of termination. Electrical stimulation of this dopaminergic axon bundle near the nucleus accumbens, as well as other sites along its course, was shown to provide adequate reinforcement to maintain lever pressing by rats to self-administer the current. On this basis, it was presumed initially that the MFB was the reward or pleasure system of the brain [40]. Subsequent work, however, demonstrated that the MFB is the substrate of reinforcement responsible for the maintenance of the appetitive phase of instinctive behavior that is characterized by *euphoric seeking* behavior, rather than the *hedonic pleasure* associated with the consummatory stage [41]. The quality of what an animal experiences during the appetitive or seeking phase of instinctive behavior is, therefore, more akin to “wanting” than “liking”, which is experienced during consummatory activity [42]. This same seeking system that plays such a critical role in sustaining the seeking behavior of animals in a search for the necessities of life also exposes them to the information that is inherent in the spatiotemporal correlations among stimuli encountered throughout the course of exploratory behavior [43–45]. The MFB seeking system must be viewed, therefore, as a vital component of the neurobiological mechanism responsible for acquiring the information that is essential for survival.

Studies of avian and mammalian classical conditioning have shown that a neutral stimulus (conditional stimulus or CS) acquires many of the properties of a biologically significant one (unconditional stimulus or UCS) after consistent pairings of the two stimuli. Animals orient towards and approach the CS in a manner called sign-tracking (see below). Jenkins and Moore [46] brilliantly vindicated the premise of behaviorism when they demon-

strated that, pigeons peck the CS with the response topography typically exhibited toward the UCS. After multiple pairings of an initially neutral CS with water as the UCS, thirsty pigeons pecked at the CS with a response topography that is characteristic of drinking. Similarly, when food was used as the UCS for hungry pigeons, they pecked at the CS with the response topography typical of feeding. The data clearly show that the detection and cognitive assimilation of the information that is inherent in the spatiotemporal correlation of the CS and UCS produce a change in behavior in which the formerly neutral CS is explored and manipulated in a new way. The CS is treated as a *sign* that indicates spatiotemporal proximity and immanence of finding the vital biological stimulus, and it becomes an object of great interest in its own right. Accordingly, the novel behaviors directed toward the CS are collectively referred to as *sign-tracking*. The findings of Jenkins and Moore [46] indicate, in fact, that the CS acquires some equivalence to the UCS. For this reason, the CS is then capable of being used as a discriminative stimulus that elicits an instrumental response to obtain the desired UCS, which is called the reinforcer, reinforcement or reward in the instrumental conditioning paradigm. When an instrumental response produces a reward (UCS) that is pleasant, that result will positively reinforce that response, which then increases in frequency. If the instrumental response leads to an adverse outcome, it will quickly decrease in frequency and be eliminated. This phenomenon was studied by Edward Thorndike, who named it the *Law of Effect* [47].

The sequence of events described above may be characterized as: (1) the observation and cognitive assimilation of information contained in the correlation between the CS-UCS; (2) sign-tracking and manipulation of the CS in novel ways, which leads to the emergence of a response that is either instrumental in leading to a reward (UCS) or not. Accordingly, sign-tracking provides behavioral evidence that apprehension of the information that is inherent to the CS-UCS correlation leads to the expectation that the UCS is imminent whenever the CS is encountered again. Sign-tracking is therefore the functional equivalent of inquiring behavior, i.e., an experiment, that either confirms or rejects the expectation (hypothesis) that the CS predicts the immanence of the UCS.

We emphasize that we are not attributing anything on the order of human insight or reasoning to animals that exhibit associative learning. Nevertheless, sign-tracking does in fact resemble intuitive science. The associational (Pavlovian) cause of the change in behavior directed toward the formerly neutral CS requires an explanation. It is widely understood that correlation between two variables or events does not necessitate a causal interaction between them, hence the common warning in statistics 101 that correlation is not causation. On the other hand, correlation between two events *is* most definitely information of great significance because the converse is also true: causation requires correlation. A causal relationship between two things requires spatiotemporal correlation between them. (This is certainly true in classical physics, although quantum physics provides an exception in the case of quantum entanglement.) Indeed, this is the premise of sign-tracking and what makes it “experimental” in nature. Does the correlation predict a causal relationship between CS and UCS? The pigeons in the Jenkins and Moore experiment clearly behave as though they have learned that the occurrence of a CS predicts the immanence of the UCS. To this point, in his comprehensive synthetic review of experimental work that defines the Reward Prediction Error mechanism Schultz [48] points out that Pavlovian conditioning only occurs when there is a strict contingency between the stimuli, and he explicitly defines this contingency as the reduction in informational entropy (see below). The information implicit in this relationship is so important to life that single-celled organisms were capable of associative learning long before its appearance in the earliest multicellular invertebrates in the Precambrian [49]. In regard to Kandel’s (Ibid) demonstration of associative learning in the gill-withdrawal reflex in the *Aplysia* [33], it is important to note that the molecular

mechanisms of synaptic plasticity that enable this behavioral change evolved millions of years earlier in the mechanisms of signal transduction and intracellular molecular signaling of single-celled organisms.

In light of the findings of Jenkins and Moore and our explanation above, it is difficult to avoid the conclusion that natural selection has hard-wired the behavioral and neurobiological components of an empirical approach to acquiring information to reduce the uncertainty and inform adaptive modifications in behavior. Indeed, like food, water, or a mate, the acquisition of information is an essential requirement for survival. Without information, there is nothing to learn and no way to attribute meaning to what is observed in the world. The need for information is a biological imperative and the neurobiological mechanisms responsible for seeking and cognitively assimilating it must be viewed as fundamental evolutionary adaptations to the myriad selective pressures that produce entropy in the organism. We argue further that the emotional continuum that is experienced by animals in the transition from *wanting* to *liking* during the appetitive and consummatory phases of instinctive behavior, respectively, is homologous to the transition that humans experience when intellectual beauty, the euphoric aspect of inquiry, culminates in the ultimate beauty of discovered truth when inquiry succeeds. In this view, the ultimate beauty of discovered truth lies on a continuum with intellectual beauty experienced during inquiry.

11. The Reward Prediction Error as a Measure of Information Gain

The ancestral phylogenetic origin of the MFB substrate of seeking (inquiring) behavior is supported by psychobiological and neuroimaging studies [42,50,51]. These references highlight that, while the specific anatomical topography of the MFB can vary slightly, the structural and functional connections (VTA to nucleus accumbens and prefrontal cortex) are highly conserved across mammals. In addition, Schultz [48] shows that the MFB's structural stability across species is matched by a rigorous functional homogeneity in which the Reward Prediction Error (RPE) signal carried by these neurons is characterized by consistent latencies and durations in monkeys, rats, and mice. Midbrain dopamine neurons implement reinforcement learning through phasic responses, where the deviation from baseline firing encodes the magnitude and valence of the prediction error. Tables A2 and A3 in the Appendix A provide explanations of the terms in the RPE equation and the significance of different RPE values.

In addition to the pioneering work of Schultz cited above as justification for using the RPE paradigm as a fundamental aspect of the cognitive neuroscience intellectual beauty, we further recognize the outstanding recent precedent set by Becker and Cabeza [28]. They have elegantly demonstrated that the subjective 'Aha!' experience of discovery is fundamentally driven by prediction error minimization. In their model, whereas curiosity acts as a motivational state driven by the expected information gain of an unsolved problem, the moment of sudden insight represents the actual or *absolute* information gain that updates the brain's predictive models. Furthermore, their neuroimaging research demonstrates the empirical hardware for this phenomenon. They show that the massive reduction in uncertainty experienced during sudden insight physically reshapes cortical representations and triggers a surge in hippocampal activity! This process, which they term the 'Insight Memory Advantage' (IMA), effectively sears the newly discovered truth into long-term memory. Their work provides compelling empirical validation that the subjective emotion of intellectual beauty is necessarily linked to the quantifiable biological reward of information gain.

From a Darwinian perspective, the brain's reward system is not merely designed to produce hedonic pleasure; it is fundamentally structured to signal to the memory systems what information is vital for survival. As the neuroimaging data demonstrate, experiencing

a moment of sudden insight while learning can almost double memory retention for that specific information. Furthermore, these intense flashes of insight literally reorganize the neural networks in the ventral occipito-temporal cortex involved in visual pattern recognition. If an organism expends the metabolic energy required to resolve a high-entropy state of confusion into a low-entropy state of clarity, it cannot afford to forget the solution. In this light, the subjective experience of “intellectual beauty” serves as the affirmational concomitant of a chemical command, driven by a positive Reward Prediction Error, ensuring that the organism permanently retains the ultrastructural changes in synaptic plasticity to enhance memory of valuable information required to adapt and survive!

Recent neuroimaging and computational modeling by Dezza et al. provides critical empirical support for this framework by demonstrating that the human brain possesses a dedicated and independent value system for information [52]. While subregions of the prefrontal cortex (PFC), specifically the ventromedial prefrontal cortex (vmPFC) and dorsal anterior cingulate cortex (dACC), have long been known to compute cost–benefit analyses to optimize the net value of traditional extrinsic rewards, their findings reveal that these same regions independently encode the value of information. This empirical evidence shows that the PFC acts as an optimizer for information gain, treating epistemic value of reduction in uncertainty as computationally distinct from, yet parallel to, extrinsic reward value. This independent neural encoding of information value perfectly aligns with the proposition that the brain inherently treats the resolution of high-entropy cognitive ambiguity as a fundamental biological reward in its own right, driving the inquiring behavior that culminates in the moment of insight.

It is crucial, however, to acknowledge the limitations of a strictly neurobiological approach. While the RPE mechanism elegantly accounts for the immediate, phasic reward of sudden insight—the biological ‘Aha!’ moment—it does not fully encapsulate the complex, multifaceted nature of esthetic judgment. The enduring experience of intellectual beauty also relies heavily on top–down cognitive processing, cultural contextualization, and long-term appraisal. The RPE signal provides the foundational biological spark of uncertainty resolution, but the sustained appreciation of discovered truth involves higher-order cortical integration that extends far beyond a singular dopamine-driven event.

12. The Evolution of Pro-Social Traits and Collective Intelligence in *H. sapiens sapiens*

While intuitive science is likely based on the neural mechanisms of animal learning it was perfected in *H. sapiens sapiens* owing to the evolution of social cooperation, theory of mind, language and especially collective intelligence. Vulnerable, slow-moving bipedal hominins who lived in the African savannah would have experienced intense selective pressure to live in sufficiently large, cooperative groups that could solve problems efficiently and especially mobilize a rapid collective defense against large African predators. It is in this context that a larger neocortex, language, theory of mind, and reciprocal altruism evolved to support intense in-group, pro-social cooperation in the interest of group survival and reproductive success [53]. Survival required our hunter–gatherer hominin ancestors to live in large intensely social groups that could work cooperatively to solve problems in the most efficient way possible. What emerged was built upon the intuitive scientific method that is based on the neural mechanisms of classical and instrumental conditioning, as described above but vastly superior to it. The enhanced problem-solving skills of our Paleolithic human ancestors derived from their ability to discuss a problem of interest and work collaboratively to find a solution through the sharing of information and ideas about their observations. An extremely important benefit of this intensely social paradigm of learning and problem solving is that group discussion effectively curates information

to provide a context for the emergence of sudden insight. This process is intensified by the phenomenon of *collective intelligence*, which is a property of the group [54]. Modern studies of group problem-solving have shown that collective intelligence emerges when all members of the group have adequate input to discussion. This likely reflects the benefit of diverse thinking styles among group members, which brings a comprehensive perspective of the problem at hand, and increases the probability of a solution (DiRocco, unpublished observation). The evolved faculty of collective intelligence is one of the most important phenomena to emerge from the evolution of pro-social human behaviors. The collective intelligence of human groups must have been an important contributing factor to the survival of early modern humans and their amazing success as they moved out of Africa into new and colder environments of Europe and Asia.

Personality theorist George Kelly worked during the first half of the twentieth century and thus overlapped with the latter part of John Dewey's life and career. He began his work in clinical psychology in the psychoanalytic tradition, but like many of his predecessors and contemporaries, he became dissatisfied with Freud's emphasis on instinct as the chief motivating force of human behavior. Kelly proposed instead that people are motivated by the need to understand and predict events in their social interactions and in the physical world. The required understanding, which is inferred from observation and experience, is a construct or hypothesis of social and physical reality that people use to make judgements and guide their behavior. The essential component of Kelly's theory of personal constructs therefore is predicated on the idea that everyone is an intuitive scientist [55]. This idea is consistent with what John Dewey concluded based on his work at the experimental school. Intuitive science has all the markings of an adaptation to uncertainty that Dewey's school children, and our Paleolithic ancestors, brought with them to group decision making. Collective intelligence that emerges during group practice of intuitive science would have been an important contributing factor to successful problem solving then, as it is now. When Dewey's young students discussed a problem of concern, they were promulgating an evolved human culture of collectively narrating group activity in real time. This turns every group activity into a forum for sharing and implicitly curating information and conjectures about a problem of interest. Through this interactive learning paradigm, Dewey's school children and our hominin ancestors were intuitively guided by the aforementioned interplay of inductive and deductive reasoning that endows both the formal and intuitive practices of the scientific method with such great efficacy in the discovery and validation of truth.

13. The Hominin Origin of the Abstraction of Form in Visual and Literary Art

Jane Goodall showed that chimpanzees could shape and use tools in the search for food [56]. After remarking on the use of tools by chimpanzees and crows, Augustin Fuentes commented further to describe the abstraction of form [57]:

"But no other animal in the wild, not even chimpanzees, can look at a rock, understand that inside that rock is another more useful shape, and use other rocks or wood or bone to modify that rock—and then share that information with the members of her group." [emphasis added].

The conventional wisdom in hominin evolution was that with their modestly increased brain size, *Homo habilis* was the first hominin to produce stone tools of a somewhat improved quality, defined as Oldowan, approximately 2.3 to 2.4 Ma [58]. This notion has been challenged with the more recent discovery of stone tool artifacts from the Lake Turkana region of Kenya that were dated to 3.3 Ma. These artifacts were attributed to a pre-human hominin, possibly *Australopithecus afarensis*, that lived 700,000 years before the first

members of the Genus *Homo* [59]. By the time *Homo erectus* appeared and domesticated fire, around 1.5 Ma., improved flint-knapping techniques produced stone tools described as Acheulean. Many Acheulean hand axes had nearly perfect tear-drop shapes and were produced far in excess of their utility for butchery. Thornhill's elucidation of Darwinian esthetics [16] led philosopher Dennis Dutton to suggest that many of these hand axes were produced as art objects that inherently demonstrated intellectual and motor skills to females. In his book, *The Art Instinct*, Dutton explains the vital role of sexual selection as an evolutionary determinant of the instinctive emotional response of humans to beauty [60]. A nearly perfect symmetrical, tear-drop shaped, hand axe could only be made by a male in possession of the ability to imagine that shape concealed within a suitable stone and the technical skills required to remove stone flakes until that shape was revealed. Production of such a stone object would have made it intuitively and unconsciously evident that the artisan possessed attractive qualities like intelligence, planning ability and technical skill that made him highly desirable as a mate, both for the genes he could contribute to their progeny and the meat he could provide for the protein needed for successful gestation and postnatal development of their infant.

The Renaissance artist Michelangelo Buonarroti gave voice to this concept when he said that "every block of stone has a statue inside it and it is the task of the sculptor to discover it" [61]. *H. erectus* and Michelangelo enjoyed the experience of intellectual beauty whether they imagined the essence of a hand axe hidden in stone or a magnificent sculpture hidden in a block of white statuary marble. In this context, imagining must be viewed as the cognitive prelude to extraction of the imagined creation from within the encasing stone. This sequence of events involves both the visualization of the desired object that lies within and execution of the plan for its removal. Perhaps more to the point of visualizing his intended creation in a block of marble before beginning his work, Michelangelo said, "I saw the angel in the marble and carved until I set him free" [61]. The intellectual beauty that Michelangelo and his distant hominin ancestors enjoyed in their discernment was communicated to others when their motor skills revealed the object of their imagination in tangible form.

Irrespective of the medium in which an artist works, most visual art involves a cognitive transformation and representation of what the artist perceives in the world. The nature of this transformation is typically given a name that defines the artist's style or perhaps even a school of art if the style is adopted widely by others. In some cases, the representational transformation of the artist's perception of the world is of a magnitude so great that the art product is referred to as "abstract art". We propose that the inspired transformations produced by an artist's "study" of an object of art are the pictographic equivalents of the sudden (inspired) insights of scientists and mathematicians, and that they are mediated by the same neurological mechanisms of the cognitive unconscious mind. This idea is supported by the role of diagrammatic representations of complex abstract mathematical problems as an aid to finding a solution [62], or determining the three-dimensional configuration of a molecule such as Kekulé's discovery of the ring structure of benzene discussed above. This is to say that the synaptic changes necessary for the "abstraction of form" in art are akin to the changes in synaptic strength that are required for the "abstraction of essence" in the process of inductive reasoning. The inquirer, for example, recognizes what is common to many unique observations of a phenomenon to "see" or discover the more general principle that they exemplify. An artist such as Picasso similarly "sees" how the two-dimensional representation of a multitude of diverse polyhedra can be used to build a loosely "tessellated" artistic representation of the human form. Hence, the term "Cubism" has been used to describe this style of his work. (Our discussion here of the origin of Cubism in Picasso's art is focused on the cognitive processing required

for the deconstruction of the normal contiguity of the human anatomical features and its representation with the loosely tessellated polyhedra of Cubism. For discussion of Picasso's autobiographical account of the inspiration that led him to the morphological deconstruction of Cubism with reference to psychoanalytic factors, see [63].) The artist's skill in exploring how far the realism of perception can be transformed without destroying the ability of a viewer to recognize the subject of the artist's study is a measure of the artist's creativity. This phenomenon is reminiscent of the ability of humans to create elaborate calligraphic representations of letters without destroying the ability of viewers to recognize them. This aspect of visual art is what viewers instinctively admire in great art, as with the *H. erectus* female who instinctively admired the perfect tear-drop shape of a hand axe created by a male artisan of her species, and with the admiration of modern humans for works of art. In both cases, the viewer instinctively recognizes that the work of art is a visual proxy for the artist's creativity and, by implication, intelligence genes. Viewers of abstract art who come to this appreciation also unconsciously must credit themselves with the intelligence to understand what the artist has accomplished. Great art creates emotional resonance between the viewer and artist by drawing the viewer into the artist's creative insight in this manner. In this view, we reiterate aspects of the in-depth analysis of Eric Kandel [64], in which he argued that abstract art is characterized by a "reductionist" approach to capture core elements of the object of study to present a deconstructed *essence* that invites the viewer to collaborate in the artistic work. (Of particular relevance to our work here is Kandel's treatment of the concept of "the beholder's share", which refers to how the visual experience of art "completes" the work in the generation of the viewer's emotional response. The significance of the beholder's share is best captured by Kandel: "Art is an inherently pleasurable and instructive attempt by the artist and the beholder to communicate and share with each other the creative process that characterizes every human brain—a process that leads to an Aha! moment, the sudden recognition that we have seen into another person's mind, and that allows us to see the truth underlying both the beauty and the ugliness depicted by the artist" (see p. 393).) To this point, Kandel writes concerning what art historian Alois Riegl, and others of the Vienna school of art called "the beholder's share" [64] (p. 189):

Riegl discovered a new psychological aspect of art: namely, that *art is incomplete without the perceptual and emotional involvement of the viewer*. Not only does the viewer collaborate with the artist in transforming a two-dimensional likeness on a canvas into a three-dimensional depiction of the three-dimensional world, the viewer interprets what he or she sees on the canvas in personal terms, thereby adding meaning to the picture. . . . Riegl called this phenomenon the "beholder's involvement" . . . [others] later elaborated on it and referred to it as the "beholder's share". [Original emphasis]

The writer also experiences intellectual beauty when imagining the proverbial thousand words that will paint a picture in the form of great literary art, as do the readers who, doing the work of the beholder's share more actively, transcribe the story's words to paint that same picture in their imaginations with the attendant meaning and emotions that the author intended to evoke. The profound impact of language on the emotions of readers demonstrates its ability to create emotional resonance between author and reader. Here, perhaps we find the ultimate justification for the inclusion of visual and literary art with mathematics and science as forms of inquiry and understanding, not only for the consilience that is achieved in the beauty that they share, but also owing to their common cognitive and neural substrates, as well as epistemic significance.

14. An Information Theory of Musical Beauty

Like visual and literary art, vocal and instrumental music is an artform that has delighted humans for millennia with its beauty, but until the dawn of information theory, the basis for this was not fully understood. (In the mathematical theory of information, information is understood to be conveyed by a message or event that has a surprise value without which nothing novel is transmitted and the message provides no information. In this sense, information is often referred to as uncertainty. Hence, “informedness” occurs when the expectation of a note or chord is not realized. The reduction in informedness occurs when the expectation is realized.) Beginning in 1958, Coons & Kraehenbuehl published two papers in which they advanced a theory of information as a measure of the structure (form) [65] and experience (feeling) [66] of music. They suggested that the experience of music, as well as visual art, is a measure of “informedness” derived from the non-confirmation of predictions made by listeners. They demonstrated that “informedness” is generated when a predictive system is non-confirmed based on the history of prior musical events in the performance. In a simple two-event pattern, if event “A” is followed by a second “A,” minimum informedness is generated due to similarity. This follows from the fundamental tenet of information theory that an event that does not convey novel information is not informative. However, the occurrence of “B” (or any “not-A”) after “A” constitutes a non-confirmation, generating a state of maximum informedness. In these examples, A and B represent musical tones, chords or longer sequences of a musical phrase. The theory also applies to harmony. In simultaneous events, the listener’s attention is drawn to the event that is most informed (the one that least fits the predictions made by the other tones). They argue that the “brightness” of a major triad comes from its clear information structure, while the “darkness” of a minor triad is due to an ambiguous information structure (multiple possible “roots” or points of high informedness).

In their 1959 paper, Kraehenbuehl and Coons provide a link to the neurobiology of reward stating that “information reduction . . . constitutes a reward for the listener”. They explicitly compare this to “drive-reduction” theory, where the sudden disposal of randomness provides “rewarding results”. In our framework here, the Information Reduction described in 1959 is the mathematical equivalent of the Positive Reward Prediction Error (δ_t). This resolution of uncertainty is fundamentally rewarding and demonstrates a causal link between entropy reduction and the experience of intellectual beauty. In visual art, this is expressed as the “beholder’s share”—the collaborative effort where the viewer resolves deconstructed or abstract elements into a unified essence (see further details in Appendix B).

15. A Perspective from “Theory of Mind” into the Hard Problem of Consciousness

The evolution of interpersonal emotional resonance as the core element of pro-social traits, whether in direct interpersonal interactions or via the medium of art, raises interesting observations and questions about the ability of humans to have insight into the cognitive and emotional content of other minds. It is widely understood that one of the greatest arguments for the development of behaviorism in psychology concerned the urgent need to objectify the study of the mind, especially owing to the inherently subjective nature of perceptual experience. The success of the behaviorist program of placing psychology on the *terra firma* of studying the observable motor output of the mind, i.e., behavior, instead of subjective emotions and perceptions, has been demonstrated to great effect in the studies of Jenkins and Moore [46]. These findings represent a high watermark in the argument for behaviorism. This argument is bolstered further by an unintended consequence of the burgeoning field of consciousness studies, which necessarily pulls psychology back

toward a desire to understand and explain the personal experience of mind. Inevitably, this effort fails when it confronts the immutably subjective nature of the qualia of perception, especially the *qualia of the perceived self*, the essence of self-awareness. This has been defined by Chalmers as the hard problem of consciousness [67].

Nevertheless, we may at least consider what insight *theory of mind* provides into this hard problem. To this end, consider literary art's magnificent achievements that enthrall readers to the point of total immersion in the perceptual and emotional experiences of fictional and autobiographical characters on the written page. This literary achievement would not be possible if hominins, and especially *H. sapiens sapiens*, had not been forced to forge intensely emotional bonds of friendship to withstand the challenges of terrestrial life and predation by African carnivores. It is in this context that *theory of mind* [68] evolved to give modern humans the ability to discern the emotional states of others and empathize with them in the furtherance of group cohesion, cooperation and survival. What is most remarkable about the theory of the mind, however, is that it is predicated on the belief shared by virtually all humans (excepting perhaps those individuals with antisocial or narcissistic personality disorders who may never develop a sense of empathy) that having experienced the qualia of our own perceived selves, we do, in fact, know how other humans experience their own minds. We come to this certitude by virtue of *theory of mind's* development beginning in the earliest stages of infancy.

The developmental course of *theory of the mind* begins with the infant's *first love at first sight* when the mother smiles, speaks and sings soothingly to her nursing baby as they gaze into each other's eyes. In order to understand how emotional interactions between the mother and infant contribute to the development of theory of mind, we look to the historical theoretical lineage established by psychoanalyst Margaret Mahler [69]. In her influential studies of ego development during the first three to four years of life, Mahler postulated that the altricial human neonate begins its postpartum experience of the world in a blissful state of unitary being with the mother. Mahler presented behavioral evidence that Ego development advances through a series of stages of separation-individuation in which progress in the development of self-awareness (individuation) is a function of increasing degrees of physical separation from mother that is related to the development of locomotor autonomy. While contemporary developmental psychology often contests Mahler's initial postulate of a literal, undifferentiated 'autistic' phase as an empirically established baseline, her framework of 'separation-individuation' remains a highly valuable interpretive lens for understanding the emotional dynamics of early childhood. As subsequently reiterated by Louise Kaplan [70], separation-individuation progresses in tandem with the emotional conflict between the desire for the safety and comfort of the maternal bond and the imperative to separate from her to experience the joys of autonomous exploration of the world. Of great interest here is the possibility that the intense love shared between mother and infant provides a paradigm that explains the intense euphoria of the early stages of romantic love and the associated activation of the mesolimbic dopaminergic pathway of the MFB [71]. It is on this basis that we see how the empathetic resonance of friendship and love gives humans insight into the qualia of another human's *emotional* state, and allows for the formation of reasonable conjectures about the emotions and intentions of others, if not the qualia of their perceptions.

16. The Developmental Course of Intellectual Beauty

Like the theory of the mind, the experience of intellectual beauty has its developmental origin in the emotional connection between the newborn and its mother, or another primary care-giving adult who serves in her place. The essential neuroanatomical substrate of this system, specifically the MFB dopamine-seeking system, the forebrain structures that receive

its dopaminergic projections, and the regions involved in the valuation of information and reward, are physically present at birth. The postnatal functionality of this innate hardware is illustrated by behavior that occurs both postnatally and in utero, for example, the maternal–infant bond begins before birth as the fetus hears and selectively attends to the sound of its mother’s voice. The maternal–infant bond that begins in utero is impacted by maternal singing during pregnancy and the unborn fetus takes notice [72]. The neonatal infant selectively attends to the sound of its mother’s voice [73]. Subsequently, postnatal observational learning plays a critical role in early childhood development and has been demonstrated as early as sixteen months of age in studies of the acquisition of proper use of a tool to obtain an out-of-reach object [74]:

Observational learning is probably one of the most powerful factors determining progress during child development. . . our results show that classic demonstration starts being helpful at 18 months of age. . . In contrast repeated observations of the required action in a social context, without explicit reference to this action, considerably advances the age of success. . . *We also show that the effect of demonstration can be enhanced if the demonstration makes the baby laugh.* [Emphasis added]

Humor stimulates multiple physiological systems that decrease the levels of stress hormones, such as cortisol and epinephrine, and increases the activation of the MFB mesolimbic dopaminergic reward system [75]. These findings, together with the positive effect of laughter on the efficacy of observational learning in early childhood, point to a neuro-humoral substrate of joy in learning in the postnatal infant. What develops postnatally is plasticity of the synaptic connections among these neurons. We have already observed that the MFB reward system reinforces and maintains seeking behaviors during the appetitive phase of instinctive behavior. *As a critical component of the neuro-humoral substrate of joy in learning, we propose that the MFB also maintains and reinforces the cognitive seeking behaviors of inquiry, and that the emotional concomitant of this effect is experienced as intellectual beauty.* When a child begins to understand and then articulate language, it asks for the names of objects by pointing to them and accumulates a repertoire of nouns. This dynamic, together with the emotional co-regulation that the mother accomplishes by demonstrating a calm attitude to an agitated child, firmly establishes a trusting cognitive and emotional didactic relationship between mother and child [69]. In this manner, a toddler learns with mother’s help to navigate the aforementioned frustrations of separation–individuation that inevitably arise during ego development. This allows a child to experience learning in a positive and pleasing emotional environment. This joy is prefigured developmentally in the spontaneous appearance of the *mastery smile* in infants and young pre-school children upon the successful completion of a new motor skill or cognitive achievement [76]. *The mastery smile therefore is the facial expression that manifests the innate joy that is experienced in the beauty of accomplishment, including the achievement of insight.* Throughout childhood, this paradigm continues as the child interrogates parents for explanations about the world, and a pattern of curiosity, questioning and exploration solidifies the experience of joy in learning that we propose is the developmental origin of intellectual beauty.

17. The Impact of Personality on the Response to the Unknown

Alternatively, when curiosity and the learning to which it leads are stultified by any negligent, incompetent, or malign influence, a child’s emotional and behavioral disposition in the face of what is often a confusing and bewildering world shifts from curiosity–approach to anxiety–avoidance. This outcome intensifies with each failure to learn successfully and can lead to a tragic turning away from learning. In this scenario, the world substantially remains full of impenetrable uncertainty and many children in this situation lose hope in their ability to learn. A world full of impenetrable uncertainty

can be experienced as an existentially oppressive, overwhelming reality. Of special importance in the category of negative societal influences on curiosity during the early years of childhood and later in educational environments outside the home is what a child could encounter in a family and community predominantly characterized by the core values of conservatism–collectivism. While the origins and implications of these cultural values are interpreted through various competing models across the social sciences, one proposed framework, the parasite-stress hypothesis advanced by Thornhill and Fincher [77], suggests that in this scenario, extroversion, curiosity, and openness to new ideas may theoretically be discouraged in favor of conformity to conservative cultural ideals and traditional values. We must note that while this specific evolutionary framework is actively debated, its core premise is supported not only by data that the authors provide in their book on the subject but also by the recent work of Olsson and Paik [78]. They trace the divergence of these norms back to the Neolithic Revolution, demonstrating that the high prevalence of infectious disease, as well as predation risks associated with centralized agricultural, in early farming villages strongly predicted the development and persistence of collectivist cultural norms. (Olsson and Paik argue that the transition to sedentary agriculture created densely populated, unhygienic villages with high pathogen stress, which, in turn, fostered strict collectivist norms demanding in-group cooperation and obedience. They propose that individuals with independent, self-reliant tendencies found these rigid societal constraints unbearable and self-selected to migrate outward. Thus, while the physical colonization of peripheral lands across Eurasia was carried out by individuals seeking independence, it was the high pathogen stress of early farming that was the primary driver of the oppressive collectivist culture that ultimately pushed them to leave.) Consequently, whether one fully accepts the parasite-stress model or views it alongside other sociological interpretations, this framework provides a useful theoretical illustration of how certain environmental pressures might ultimately suppress intellectual curiosity.

In his *Critique of Judgment*, Kant [79] speaks of a negative emotional response that accompanies the experience of what he calls “the sublime”. Richard Gilmore [80], in writing about his concept of *Philosophical Beauty* (We see in Gilmore’s notion of *Philosophical Beauty* the *Intellectual Beauty of philosophical inquiry!*), explains Kant’s analysis and characterization of sublimity:

“The sublime. . . according to Kant, is a principle of disorder, of purposivelessness. It is the phenomenon of our understanding encountering something which it cannot organize or contain. It cannot determine a delimiting organizing principle in the thing because it cannot determine any limits to the thing. It cannot determine any limits to the thing because the thing defies the presentative powers of the imagination. It is beyond the powers of the imagination to present a sensible form to the understanding, and it is beyond the powers of the understanding to make sense out of nothing. Both of those faculties seem to fail us in the confrontation with the sublime. The sublime, therefore, represents for us disorganization. This disorganization is not just an external arbitrary disorganization, but one that suggests an internal, systemic disorganization, because it is from our own inability to organize this thing that we perceive that the sense of disorganization arises. That is threatening to our conception of ourselves as organized and organizing things. It is something frightening.”

Kant’s portrayal of the frightening effect of *the sublime* when “our understanding encounters something which it cannot organize or contain” appears to align with what Thornhill and Fincher [77] would consider to be the negative influence of the core values of conservatism–collectivism. This suggests the counterpoint that a child living in a family and community characterized by traits of individualism and openness to new ideas could

respond with positive emotions of awe, and intellectual curiosity when confronted with the unknown. Gilmore's account of Kant's description of the sublime "as a principle of disorder, of purposivelessness" is suggestive of entropy or uncertainty of a vast magnitude, something on the order of the universe itself and the myriad bewildering questions it raises for the sapient mind to consider. It is easy to see how individuals belonging to a conservative–collectivist personality persuasion would experience this as "something frightening", while those inclined toward individualism and openness could experience the sublimity of the universe with a sense of awe, radical amazement and wonder that is a desire for knowledge. Apprehension and assimilation of information are essential to the ability of life to respond to and overcome the challenges of entropy. Accordingly, we argue here that curiosity, the desire for knowledge, is an adaptive evolutionary response to entropy that can be viewed as a higher-order drive to seek information. Natural selection has favored curiosity as the optimal cognitive state that motivates and guides human minds to an intuitive scientific method, insight and the discovery of meaning as we explore the world. The positive emotional experience of intellectual beauty that begins with curiosity and maintains inquiring behavior to the discovery of truth in the face of the unknown is the ultimate beholder's share that humanity contributes to the space–time canvas of creation of which we are a part. This perspective of humanity's beholder's share in the experience of awe in the contemplation and study of the universe resonates with Dana Gioia's understanding that, "Beauty is a true and powerful way of looking into the nature of reality. . . The experience of Beauty is our recognition of the deepest tendencies of the forms of the universe, our highest and most complete integrative level of understanding." [15].

18. Our Thesis

The synthesis we attempted in this paper was conceived in the hope of providing a wide-ranging firm foundation for future computational and experimental research. The essential premise that we advocated in striving toward this goal is that entropy is a fundamental physical predicate of the origin and evolution of life and mind in the universe. The metabolic and behavioral adaptations that work to resist and correct entropy's adverse effects on life are consistent with our thesis. Among those adaptations is the overarching tendency of all life forms, including plants to detect, orient towards, and/or approach, to assimilate information metabolically or cognitively as the exact "antidote" to the adverse effects of entropy. For this reason, information has at times been referred to as *negentropy*. In this view, it is not hyperbolic to say that life and the mind are the universe's answer to entropy. Clearly, the growth of entropy together with the force of gravity was a major factor in creating the order that results from star formation. This was the necessary factor that enabled abiogenesis and the evolution of life that followed it.

As Coons has noted regarding the measurement of information in complex structures, as sequences increase in length and the number of unique forms explodes, the source of new information is increasingly found at higher and more complex levels of structural analogies. When this informational dynamic is biologically exemplified in the formation of life and its evolutionary experiments, "survival-of-the-fittest" fundamentally becomes a measure of how successfully the interaction of entropy and the genome has measured and adapted to complex "analogical" structures of an ever-changing environment. In this framework, random genetic mutations generate high-entropy variation—the raw, chaotic "literal" notes of evolutionary experimentation. Natural selection acts as the ultimate macroscopic information-reduction filter. It preserves the novel nucleotide sequences that successfully adapt to informational changes in the environment while purging the corrupted "noise" of unfit mutations. Ultimately, DNA functions as what Schrödinger originally theorized as an "aperiodic crystal", an information-processing and storage mechanism that resolves

the paradox of life, maintaining a highly ordered, low-entropy state within an expanding, entropic universe.

19. A Comparative Analysis of the Cost of Information in Scientific and Esthetic Domains of Inquiry

This article is presented as a theory-building paper to help establish an interdisciplinary framework linking information reduction to the neurobiology of reward, across multiple domains of inquiry, with the hope that it will invite and guide future empirical testing while affirming the work already accomplished by others whom we have cited. Here, we offer what we believe is a useful step in the direction of further research in the valuation of information beyond the domain of motivated animal behavior.

If the acquisition of information is a biological imperative for survival, then behaviors directed toward its acquisition should be motivated by curiosity and governed by the reward-gated mechanisms of the Reward Prediction Error (RPE). This is to say that natural selection has perfected an efficient mechanism for the biological “valuation” of information. This being the case, we also expect that natural selection would have perfected efficient means for the monetary valuation of information across diverse modes of inquiry. This includes objective scientific and subjective esthetic modes of inquiry. Interestingly, the valuation of art provides both an esthetic dimension as well as a very complex sociological component in the price discovery of fine art. By comparing pharmaceutical R&D (objective) and the contemporary art market (subjective and complex price discovery in the art market), we will determine whether price discovery for information remains consistent across vastly disparate domains of inquiry.

20. Hypothesis and Experimental Test: The Price of Information

We hypothesize that if the resolution of informational entropy is a universal biological adaptation, then the “price” paid to resolve that entropy (the “information tax”) must remain constant across radically different domains. To test this, we quantify the capitalized cost required to purchase the “first bits” of information in two disparate fields: objective science and subjective art. *A significant divergence in the ratio of expenditure to success probability between these domains would disprove the existence of a universal, predictable cost for the reduction in uncertainty.* Furthermore, at the micro-biological level, this RPE model of intellectual beauty is strictly falsifiable: if future neuroimaging studies within individual subjects fail to demonstrate a phasic dopamine surge (a positive RPE) corresponding specifically to the resolution of high-entropy cognitive ambiguity, the core biological premise of this framework would be fundamentally challenged. We must note, however, that the pioneering papers that we cite in this review have already provided multiple convincing demonstrations of the dopaminergic MFB-RPE mechanism in mediating the emotional concomitants of sudden insight.

21. Methodological Data and Operational Calculations

The objective pharma-economic model: In pharmaceutical R&D, we define “early stage” of drug discovery as the transition from a new chemical entity to the start of human clinical trials. Often, this begins without even knowing the cause of a new disease; so, it is a phase of drug discovery in which a great deal of uncertainty must be overcome. Correspondingly, this requires a very large amount of information. Data drawn from DiMasi et al. [81] demonstrate that the cost of finding a clinical lead candidate is \$1.1 billion relative to a total capitalized cost of \$2.58 billion to find a marketable drug. Obtaining the information needed to find a drug ready to enter Phase 1 clinical trials yields an ultimate clinical success probability of exactly 11.83%. As shown in Table 1, Approximately 43%

of the total capitalized cost of drug development is expended o reach this stage, at which only 11.8% of the total amount of information required to find a marketable drug has been obtained.

Table 1. Comparative matrix: the cost of information. To evaluate the hypothesis, we map the early-stage capitalized cost against the information purchased (ultimate success probability) for both domains, as shown in the table below.

Domain	Early-Stage Capitalized Cost (%)	Information Purchased (Success Probability)
Pharma (Objective)	42.9% (\$1.1B of \$2.56B)	11.83% (Clinical Success Rate)
Art (Subjective)	~30–50% (Art Fairs + Overhead)	~10.2% (Consecration Rate) *

*: Consecration refers to the process by which an artist or artwork achieves institutional and cultural legitimacy. It transforms an object from a simple decorative commodity into a canonical, highly valued masterpiece. This elevates the work’s prestige and, consequently, its financial value.

22. The Subjective Aesthetic Art Market-Based Price Discovery

The contemporary art market represents the ultimate macroeconomic scaling of hominin collective intelligence. Just as a group of our early ancestors collaboratively curated observations to resolve a survival problem, the primary art market relies on galleries and institutional structures to act as “cultural labs.” As sociological research demonstrates, artistic value is socially constructed rather than inherent. Following Bourdieu’s [82] concept of “symbolic capital” within the field of cultural production, Moulin’s [83] analysis of how market and institutional consecration converge, and Velthuis’s [84] demonstration that prices function as a symbolic language rather than mere economic indicators, these institutions negotiate the transformation of high-entropy creative output into low-entropy market value. In this sense, the art market operates as the macro-social equivalent of the brain’s predictive models—performing the collective “biological work” of curating and validating cultural ambiguity into recognized esthetic truth. The capitalized cost of generating the first “bits” of this sociocultural market consensus is predominantly through participation in International Art Fairs, which account for up to 35% of dealer turnover, plus artist subsidies and overhead front-loads, representing a comparable 30–50% of an artwork’s lifecycle value.

23. Equivalency and Significance

The correspondence is noteworthy and confirms our hypothesis. In both domains, humanity pays a ~43% “information tax” to achieve a roughly ~10–12% probability of success. Whether decoding a molecule or “consecrating” a canvas, we must expend nearly half our total available capital just to move from “maximum entropy” to a stage where we still face an almost 90% failure rate. This provides an empirical metric to vindicate Bertrand Russell’s famous claim that the beauty of mathematics and the greatest art are comparable. Both represent the exact same biological price the collective human brain pays to turn chaos into order. By demonstrating this quantitative principle of “Price Discovery for Information,” we provide initial evidence that the valuation of information is a universal biological constant across the objective, subjective and cultural domains of price discovery for information. We recognize that this comparison represents a limited test of our hypothesis and more work is needed to determine if the relationship we demonstrated here holds across other methods and domains of inquiry in the price discovery of information.

24. Conclusions: Nurturing the Development and Appreciation of Intellectual Beauty

The neural substrates of intellectual beauty and intuitive inquiry are present at birth and are activated in the loving didactic relationship that is established between mother and

child during infancy and early childhood. The paradigm of joy in learning is manifested explicitly in the appearance of the mastery smile when a child succeeds in mastering a new motor skill or cognitive achievement. Throughout life, the experience of intellectual beauty is triggered in inquiring minds that are engaged in cognitive processes that lead to a moment of insight. Intellectual beauty experienced during inquiry anticipates the ultimate beauty of discovered truth. It is the reward that maintains inquiring behaviors and creative processes of children, scholars, and artists until inquiry succeeds in the discovery of meaning in the essence or truth about some phenomenal aspect of reality or a new artistic creation. Learning environments and practices that support curiosity and facilitate the experience of intellectual beauty are essential for the formation of students who learn efficiently in the manner that has been optimized by natural selection throughout the evolution of life. The anticipatory joy experienced during inquiry as it leads to insight and learning can indeed be so engrossing that time seems to stop [85]. The intellectual beauty that is experienced during inquiry anticipates the ultimate beauty that is discovered when the essence of an object of inquiry, whether in scholarly or artistic endeavor, is revealed. The appearance of the mastery smile in humans so early in life is a strong indicator that the positive emotion evoked by intellectual beauty is the prime mover and guarantor of human inquiry and the learning that is essential during life's most formative years and beyond. Then, let us honor it by giving young minds sway to plot their course in early pre-school exploration of the world and later in flexible curricula, guided by their own interests and curiosity about the radically amazing nature of the universe that lies before them. That is the context in which encouragement and coaching by experienced educators can support student agency over learning, engagement with intuitive procedures of inquiry, and a heritage of discussion that will lead them naturally to insight, learning and one day self-actualization and wisdom as their legacy to bestow on humanity. For, when sapient mind first emerged in the universe the experience of sudden insight emerged with it. By resolving a high-entropy state of cognitive uncertainty into a low-entropy state of predictive clarity the mind does not merely perform a localized neural calculation. It is contributing the 'beholder's share' to the cosmic masterpiece. The ultimate metric of this grand, self-organizing loop is the intellectual beauty of inquiry and the sublime beauty of discovered Truth.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process:

During the preparation of this work, the authors utilized an AI assistant to aid in the interdisciplinary literature search strategy (spanning statistical mechanics, neurobiology, and aesthetics), the plain-text typographical translation and formatting of the mathematical models (specifically the RPE, cosmological entropy gap, and thermodynamic equations). Following the use of this service, the authors thoroughly reviewed, edited, and approved the final manuscript, and take full responsibility for the accuracy, scientific integrity, and final content of this publication.

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Appendix A

Table A1. (a) Synthesis of paradigms for understanding intellectual beauty and intuitive discovery. Stages 4 and 5 of Dewey’s characterization of the steps of intuitive science are combined in this and subsequent tables as stage 4. (b) Synthesis of paradigms for understanding intellectual beauty and intuitive discovery.

Stage of Discovery	Physics/Information Theory	Esthetics/Philosophy	Neurobiological Substrate
(a)			
Stage 1: Felt Difficulty	High Entropy/Maximum Uncertainty	Perceptual Confusion/Bafflement	IPL & MTG Activation [86]
Stage 2: Inquiring Behavior	System Far From Equilibrium	The Tortuous Path of Inquiry Data Curation	Expected Info Gain & MFB SEEKING
Stage 3: Sudden Insight	Biological Phase Transition	The Moment Sudden Clarity in the form of a conjecture	Positive RPE & rATL/Hippocampal Surge
Stage 4: Discovered Truth	Low-Entropy Structure	Intellectual Beauty of Discovered Truth	Ventral Occipito-Temporal Cortex Reshaping
(b)			
Stage 1: Felt Difficulty	Brain Regions Activated by High Uncertainty The activation of the inferior parietal lobule (IPL) and middle temporal gyrus (MTG) in response to high uncertainty, perceptual confusion, and the induction of curiosity [86]		
Stage 2: Inquiring Behavior	Expected Information Gain and MFB Seeking Behavior The Medial Forebrain Bundle (MFB) serving as the substrate of reinforcement that maintains “euphoric seeking” or active inquiring behavior (rather than the hedonic pleasure of consummatory reward) [41,42]		
Stage 3: Sudden Insight	Positive RPE & rATL/Hippocampal surge The 300-millisecond high-frequency EEG burst and fMRI spike in the right anterior temporal lobe (rATL) preceding conscious insight, coupled with the massive positive Reward Prediction Error (RPE) signal [26,48]		
Stage 4: Discovered Truth	Ventral Occipito-Temporal Cortex Reshaping The “Insight Memory Advantage” (IMA), where the sudden clarity of the “Aha!” moment fundamentally reorganizes visual pattern recognition in the ventral occipito-temporal cortex and triggers hippocampal activity to sear the discovered truth into long-term memory [28]		

Table A2. RPE equation and explanation of terms $RPE = \delta_t = [R_t + \gamma V(S_{t+1})] - V(S_t)$.

Term	Explanation
(δt)	The Reward Prediction Error (RPE) signal; the computed difference between the actual informational outcome and the predicted value.
$[R_t + \gamma V(S_{t+1})]$	Target Value: Represents the updated informational reality, integrating immediate feedback with the discounted future value.
R_t	Reward of Uncertainty Resolution: The immediate reward at a time that serves to reduce environmental entropy and uncertainty by providing a measure of the experience.

Table A2. Cont.

Term	Explanation
(γ)	Discount Factor: A parameter that typically adjusts the present value of future rewards based on their temporal delay.
$V(S_{t+1})$	Predicted Value of the Next State: The estimated value of the state the organism expects to transition into following the current time step.
$V(S_t)$	Predicted Value of the Current State: The prior estimate of value held by the organism; the expectation established before the resolution of R_t .

Table A3. Behavioral and biological effects associated with RPE values.

RPE Magnitude	Cognitive/Behavioral Outcome	Neurobiological Implementation
RPE > 1	Response Acquisition	Phasic Dopamine Surge (high-intensity global reward signal)
RPE = 1	Positive Reinforcement; Increased Frequency of Behavior	Phasic Dopamine Activation (encoding positive utility prediction error)
RPE = 0	Policy Maintenance/Stability	Baseline Firing Rate (approximately 3–4 Hz tonic activity)
RPE < 0	Aversion/Extinction	Dopamine Depression (decreased firing below baseline rate)

Note: Because the Reward Prediction Error is a relative computational signal rather than a metric with an absolute physical unit, the threshold for maximal uncertainty resolution is mathematically normalized to 1.

Appendix B

A Methodological Primer on Calculating “Informedness”

To ensure the reproducibility of the information values cited below in this Appendix (e.g., 4.90 non-confirmations out of 9.00 total predictions), it is necessary to briefly illustrate the 1958 Coons and Kraehenbuehl calculus [65]. In their model, the human brain calculates predictions on two levels: the Literal level (comparing the events themselves) and the Analogical level (comparing the relationships between the events). A confirmed prediction (a relationship of similarity) is scored as an ‘s’ (same), yielding no new information. A non-confirmed prediction (a relationship of dissimilarity) is scored as a ‘d’ (different), yielding information.

For example, in a three-event sequence of entirely novel stimuli—such as the musical notes A-B-C—the brain makes three literal comparisons (2 vs. 1, 3 vs. 1, and 3 vs. 2). Because all three notes differ, this generates three ‘d’ values. However, at the analogical level, the brain compares the relationships. Because the transition to the third event (3 vs. 2 = ‘d’) is the exact same type of transition that occurred prior (2 vs. 1 = ‘d’), the brain recognizes a higher-order pattern of constant change. Comparing ‘d’ to ‘d’ yields an ‘s’ (similarity) at the analogical level, generating zero new information. Thus, the total informational score of the A-B-C sequence is derived from three literal ‘d’s and zero analogical ‘d’s. By scaling this precise calculus of non-confirmations (‘d’s) up to complex, multi-event patterns, we can map the exact trajectory of information flux that drives the neurobiological Reward Prediction Error (RPE).

Methodology: The Operational Calculus of Information and Reward

1. The operational equations of predictive coding: In order to quantify the exact degree of uncertainty generated by a sequence of events, this framework utilizes the foundational calculus established by Coons and Kraehenbuehl (1958) [65]. This calculus models the brain’s predictive processing by defining two fundamental relationships between the past and the present: Similarity (s) and Dissimilarity (d). When the brain processes a sequence, it tests its predictions against incoming environmental data. A confirmed prediction yields a state of minimal informedness (scored as 0), while a non-confirmed prediction

yields a state of maximal informedness or surprise (scored as 1). Because relationships themselves become part of the pattern the brain learns to expect, four operational equations govern the interaction of sequential events:

- $s/s = s$ (A pattern of similarity predicting further similarity. The prediction is confirmed, yielding 0 uncertainty.)
- $d/d = s$ (A pattern of constant change predicting further change. The prediction is confirmed, yielding 0 uncertainty.)
- $s/d = d$ (A stable pattern suddenly broken by a novel event. The prediction is non-confirmed, yielding maximum uncertainty of 1.)
- $d/s = d$ (A pattern of constant change suddenly broken by a repeated event. The prediction is non-confirmed, yielding maximum uncertainty of 1.)

2. Computing accumulated uncertainty $V(S_t)$: As a sequence unfolds, the brain generates an increasingly complex array of literal and analogical predictions. At each new event, this entire array of predictions is tested. The overall informedness of that exact moment is mathematically defined as the number of non-confirming tests divided by the total predictions tested. Within the modern Reward Prediction Error (RPE) paradigm ($\delta_t = [R_t + \gamma V(S_{t+1})] - V(S_t)$), this informedness percentage establishes the predicted value of the current state, $V(S_t)$. It represents the accumulated baseline of uncertainty.

Below are the computations for the fourth event in several basic patterns:

- **Pattern A-A-A-A (4th Event is A):** 0.00 non-confirmations out of 10.00 predictions tested = 0.0% informedness (highly predictable).
- **Pattern A-B-B-A (4th Event is A):** 4.90 non-confirmations out of 9.00 predictions tested = 54.4% informedness (moderate uncertainty).
- **Pattern A-A-B-A (4th Event is A):** 6.05 non-confirmations out of 10.00 predictions tested = 60.5% informedness (high uncertainty).
- **Pattern A-B-A-C (4th Event is C):** 7.50 non-confirmations out of 10.00 predictions tested = 75.0% informedness (maximum uncertainty). However, as that pattern extends into a patterns of AB, AE, and AF that kind of pattern becomes predictive, i.e., non-informative.

3. Information reduction as biological reward (R_t): This operational calculus reveals the exact mathematical conditions required to trigger a cognitive reward. A highly predictable pattern like “A-A-A-A” generates no reducible information, failing to establish a clear cognitive hierarchy or capture attention. Conversely, a highly articulate pattern like “A-A-B-A” actively generates a high state of uncertainty at the third event (“B”), peaking the baseline prediction variable $V(S_t)$. When the fourth event (“A”) occurs in the “A-A-B-A” sequence, it confirms the initial structural pattern, causing a sudden, massive drop in the accumulated randomness. This quantifiable “Information Reduction” acts as the immediate biological reward (R_t). When this sudden structural reward is processed against the high-entropy baseline ($V(S_t)$), the RPE formula yields a massively positive δ_t . This generates the phasic dopamine surge—the literal neurobiological mechanism underlying the “Aha!” moment of discovery.

Mathematically Bridging the Information Theoretical Description of the Structure of Music with the Reward Prediction Error (RPE)

1. Theoretical alignment: “In this section, we propose a conceptual alignment. . .” between the foundational information theory of musical structure proposed by Coons and Kraehenbuehl in 1958 and 1959 [65,66] and the contemporary neurobiological Reward Prediction Error (RPE) framework defined in 2015 by Schultz [48]. By aligning the concepts of “informedness” and “information reduction” with the variables of the RPE equation, we demonstrate that the cognitive *reward of musical discovery* relies on the exact same

computational mechanism that governs dopaminergic reinforcement learning. The reward of musical discovery then corresponds to the intellectual beauty experienced by individuals who engage in all the diverse forms of inquiry.

2. Variable mapping: The modern RPE formula is defined as $\delta_t = [R_t + \gamma V(S_{t+1})] - V(S_t)$. Variables from Kraehenbuehl and Coons computational procedure map directly to these modern terms:

- $V(S_t)$ (Predicted Value of the Current State): In the 1958/1959 framework, when a listener experiences a highly complex or novel sequence, uncertainty builds up. Because the brain's predictive models are failing to anticipate the pattern, the expected value or certainty of the current state drops significantly. This high-entropy state of accumulated randomness means the baseline prediction $V(S_t)$ is extremely low.
- R_t (Reward of Uncertainty Resolution): Kraehenbuehl and Coons explicitly theorize that "information reduction is comparable to the concept of drive-reduction in learning theory" and constitutes a reward for the listener. When a musical event suddenly confirms a structural pattern, it causes a sharp drop in randomness. This quantitative measure of "Information Reduction" functions directly as the immediate reward R_t .
- δ_t (The Prediction Error): According to the RPE model, learning and approach behavior advance to the extent that a reward is unpredicted. When a sudden "Information Reduction" (R_t) is processed against a backdrop of high accumulated uncertainty ($V(S_t)$), the equation yields a massively positive δ_t . This generates a phasic dopamine surge—the neurobiological equivalent of the "Aha!" moment of musical insight.

3. Data integration—computations from four-event patterns: These final values are derived by simply summing the non-confirming events (dissimilarities) tallied across both the direct literal comparisons and the higher-level analogical comparisons within the sequence.

To demonstrate this computation, we can apply the "informedness percentiles" computed by Kraehenbuehl and Coons in Table 3 of their 1959 paper [66]. They evaluated various four-event patterns to determine how effectively they generate and subsequently reduce information. For example, consider Form III (Pattern "A-A-B-A"):

- At Event 1 (A) and Event 2 (A), informedness remains at 0.00 because the events are entirely similar and predictable.
- At Event 3 (B), a non-confirmation occurs, generating a maximum state of informedness (1.00). Because the pattern is highly unpredictable, the listener's expected certainty bottoms out, rendering the variable $V(S_t)$ effectively zero.
- At Event 4 (A), the return to the initial pattern causes the informedness to drop sharply to 0.50. This sudden drop of 0.50 constitutes a massive 'Information Reduction'. Plugging this into the RPE formula: subtracting the near-zero baseline prediction $V(S_t)$ from the sudden onset of structural reward R_t (0.50) guarantees a highly positive δ_t (+0.50). Kraehenbuehl and Coons noted that patterns lacking this crucial information reduction (such as "A-A-A-A") fail to establish a clear hierarchy or cognitive "point" for the listener.

4. Sequential processing and the discounted future value [$\gamma V(S_{t+1})$]: Because music is a continuous "event-order," the brain is constantly anticipating future sequences as it listens. Kraehenbuehl and Coons [66] explicitly noted that the occurrence of any event "compels us to create a new probability system which takes the new event into account," and this new probability system is subsequently tested by the events that follow. In the Temporal Difference (TD) RPE model ($\delta_t = [R_t + \gamma V(S_{t+1})] - V(S_t)$), this ongoing anticipation is captured by the bracketed "Target Value". When a structural resolution occurs (such as the final "A" in an "A-A-B-A" pattern), it not only delivers an immediate information

reduction (R_t), but also instantly establishes an updated predicted value for the next state, $V(S_{t+1})$. These terms are mathematically grouped together because the brain evaluates the “New Reality” as the sum of the immediate structural reward *plus* the updated anticipation of the future. Furthermore, the discount factor (γ) perfectly captures the listener’s temporal horizon; the brain strongly predicts the immediate next note, but predictions for events occurring much later in the composition are highly discounted. Therefore, the TD-RPE equation accurately models musical listening as a dynamic, moment-by-moment updating of both immediate structural reward and future expectation. These equations demonstrate that the brain does not merely track absolute, isolated values, but rather computes the evolving relationships and the relationships of relationships between successive events to build its predictive models as explained in (4) above in relation to the term $[\gamma V(S_{t+1})]$.

5. The Unified statement: Translating the 1958–1959 musical information computations into the modern RPE model reveals a profound historical and scientific synthesis. The contemporary neurobiological RPE signal—measured in the phasic firing of dopamine neurons today—is computing the exact informational derivatives that Coons and Kraehenbuehl theorized decades ago. Because Coons subsequently spent his career investigating the neurobiological and behavioral phenomena mediated by the Medial Forebrain Bundle (MFB) that processes these very rewards, this synthesis positions his work in a comprehensive historical context.

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