

NATURE & SIMPLICITY

How Information Protects Nature

A First-Principles Framework for Environmental Intelligence

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“Behind it all is surely an idea so simple, so beautiful, that when we grasp it—in a decade, a century, or a millennium—we will all say to each other, how could it have been otherwise?” — John Archibald Wheeler

Abstract

This paper presents a first-principles framework for environmental protection grounded in the deepest results of modern physics. We show that nature's complexity arises from an extraordinarily simple foundation—single binary observations (bits), accumulated one at a time through irreversible physical interactions. We derive from thermodynamics that configuring matter with information costs orders of magnitude less energy than configuring it with force—a ratio set by the laws of physics, not by technology. At the molecular floor, knowing is 268 times cheaper than moving. At the operational scale of real environmental events, this ratio reaches 10^{16} to 10^{22} , depending on scenario assumptions. We present the Boundary Dominance Conjecture—extending the holographic principle from black holes to general environmental systems—and show that for environmental systems specifically, the practical consequence follows rigorously from conservation laws: measuring system boundaries in real time, reconstructing interior states using physics engines, and steering environmental configurations with information rather than force. We describe how artificial intelligence enables this approach at planetary scale, and we argue that environmental superintelligence—a system that maintains Earth's life-sustaining configurations continuously at costs approaching the thermodynamic floor—is physically possible and thermodynamically favored.

The universe is arrangement, writing itself one bit at a time according to least action—and to protect its living arrangements, steer with information, for that is how nature builds herself.

Part 1: The Underlying Simplicity

Everything Is Arrangement

Pick up a rock. Now pick up a flower. They feel completely different. One is hard and gray and inert. The other is soft and colorful and alive. But if you zoom in far enough—past what your eyes can see, past what a microscope can see, all the way down to the atoms—the rock and the flower are made of the same stuff. Carbon. Oxygen. Hydrogen. Nitrogen. The exact same atoms.

So what makes the flower a flower and the rock a rock? The arrangement. The atoms in a flower are arranged in a very specific pattern—a pattern that captures sunlight, pulls water from soil, builds petals, and makes seeds. The atoms in a rock are arranged in a different pattern—a pattern that just sits there.

Same atoms. Different arrangement. That's it. That is the only difference between a living thing and a dead thing. Between a forest and a desert. Between a clean river and a polluted one.

Arrangement is the most important thing in the universe. And arrangement has another name. Scientists call it **information.**

This single observation—that reality is not made of things but of how things are arranged—is the foundation of everything that follows. It is the simplest idea in this paper, and every equation, every calculation, every practical implication flows from it.

Nature Builds from the Bottom Up

The double-slit experiment—arguably the most important experiment in the history of physics—demonstrates how nature works at its most fundamental level. You shoot individual photons at a barrier with two narrow slits and observe where they land on a detection screen.

If you shoot one photon, it lands in one spot. One dot on the screen. One answer. Yes or no. 0 or 1. One bit of information.

But if you shoot billions of photons, one at a time, something remarkable happens. The dots build up into a pattern—bright bands and dark bands called an interference pattern. The deepest laws of quantum mechanics appear before your eyes, built entirely from single bits. One dot at a time. 0 or 1. Over and over.

That is how nature builds everything. Not from some grand blueprint imposed from above. From the bottom up. One tiny yes-or-no answer at a time. Billions upon billions of them, accumulating into atoms, molecules, cells, organisms, forests, rivers, the biosphere.

“Nature operates in the shortest way possible.” — Aristotle

Aristotle's intuition has been formalized in modern physics as the *principle of least action*: all of classical mechanics, electromagnetism, general relativity, and quantum field theory can be derived from the single requirement that the action integral is stationary. Nature does not waste. She operates at the simplest, cheapest, deepest level available.

Part 2: The Self-Writing Universe

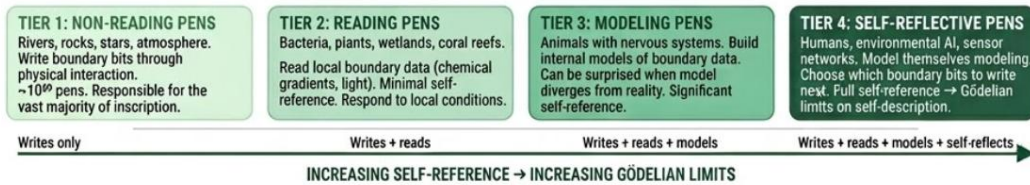
Every Interaction Writes a Bit

Every time anything in the universe interacts with anything else—a photon bouncing off a leaf, a water molecule colliding with another water molecule, a cosmic ray striking a nitrogen atom in the atmosphere—a bit is written. A previously undetermined quantum state becomes effectively determined. The universe’s arrangement becomes slightly more specific. This is the physical process known as *decoherence*, and it has been experimentally confirmed with extraordinary precision.



THE HIERARCHY OF PENS

Every physical interaction writes boundary data. What distinguishes pens is whether they read.



The universe is a self-writing manuscript. The boundary is the page. Every interaction is a stroke of ink. The observer is the pen that knows it is writing and therefore knows it cannot read the whole page.

A necessary precision: decoherence produces *effective* collapse—interference terms become negligibly small for macroscopic systems—but does not require a literal ontological collapse of the wave function. For all environmentally relevant systems, which are thoroughly macroscopic, the distinction is irrelevant. The bit is written, and it stays written.

This has been happening since the Big Bang, 13.8 billion years ago, everywhere in the universe, continuously. Approximately 10^{88} to 10^{104} bits of entropy have been inscribed over cosmic history (from Penrose’s CMB photon entropy through Egan and Lineweaver’s black-hole-dominated estimate). Each one wrote a single bit. The accumulated result is everything we observe—the entire physical world.

Everything writes. Everything is a pen. But pens differ in what they do with what they have written.

The Hierarchy of Pens

Physical systems can be classified into four tiers based on their self-referential depth—the degree to which they read and act on the information they write:

Tier	Examples	Capability	Limits
Tier 1	Particles, rocks, stars	Write only. No reading.	None—no self-reference
Tier 2	Bacteria, plants	Write and read. Respond to local data.	Minimal
Tier 3	Animals	Write, read, and model. Can be surprised.	Present
Tier 4	Humans, advanced AI	Write, read, model, and self-reflect. Choose what to observe.	Fundamental—Gödelian

Rocks write bits when sunlight hits them. Stars write bits when they fuse hydrogen. The ocean writes bits every time a wave crashes. But none of them read what they’ve written. A rock does not know it scattered a photon. A star does not know it fused an atom.

Living things are different. A bacterium reads chemical gradients and swims toward food (Tier 2). An animal builds an internal model of its environment and can be surprised when reality contradicts the model (Tier 3). And humans do something no other known entity does: we choose what to observe. We point telescopes at stars. We put sensors in rivers. We design experiments. We decide which questions to ask—and the question we ask determines which bit gets written next (Tier 4).

Entropy Drives the Writing. Dissipation Structures the Pen. Negentropy Steers It.

What drives the universe's self-writing? The second law of thermodynamics. Entropy—the total number of determined bits—never decreases in a closed system. Every decoherence event increases entropy and writes a new bit. This is irreversible: once a bit is written, it stays written. The manuscript only moves forward. The arrow of time is the direction in which boundary data accumulates. (*Why the universe began in the extraordinarily low-entropy state required for this arrow to exist remains the deepest open question in physics. The second law explains why entropy increases going forward, but not why it started so low.*)

Thermodynamic entropy and information entropy are the same quantity, measured in different units. Boltzmann's $S = k_B \ln W$ and Shannon's $H = -\sum p_i \log_2 p_i$ are related by $S = k_B \ln 2 \times H$. This equivalence was proven by Jaynes (1957), confirmed physically by Landauer (1961), and verified experimentally by Bérut et al. (2012). **There is one entropy.** It measures the same thing whether you call it disorder, missing information, or the number of yes-or-no questions needed to specify the state.

Within this entropy-producing universe, local negentropic structures arise—stars, planets, organisms, brains, artificial systems. But *why* do they arise? Erwin Schrödinger posed the question in 1944: how do living things maintain their order against the universal tendency toward disorder? His answer—organisms feed on “negative entropy” from their environment—was correct but incomplete. It explained how organisms *sustain* order, not how order *originates*.

Ilya Prigogine completed the answer. His theory of *dissipative structures* (Nobel Prize, 1977) demonstrated that systems driven far from equilibrium by continuous energy flow can spontaneously develop ordered configurations that would be impossible at equilibrium. Heat a thin layer of fluid from below, and beyond a critical temperature gradient, the fluid spontaneously reorganizes into hexagonal convection cells. Order emerges from energy flow. The Second Law, applied to open systems, not only permits local order—it can *drive* its spontaneous emergence when free energy gradients are present.

Harold Morowitz crystallized the principle: the energy that flows through a system acts to organize that system. Life is not a violation of the second law but its most sophisticated expression—structures that maintain internal order (low entropy, high information content) by consuming free energy and exporting waste heat. A human body dissipates approximately 100 watts maintaining its configuration. This entropy export is the thermodynamic cost of being alive—of being a pen that reads its own writing.

Entropy is the ink. Dissipation structures the pen. Negentropy steers the writing.

Entropy provides the drive—the universal tendency toward more inscription. Dissipation, channeled through far-from-equilibrium energy flows, provides the mechanism by which organized pens spontaneously arise. And negentropy provides the steering—the organized information processing that allows systems to read what has been written and choose what to write next. The complete picture: life is the universe’s mechanism for producing organized writing instead of random scribbling, and it arises not in spite of the second law but because of it.

Part 3: The Boundary Dominance Principle

Information Lives on the Boundary

In the 1970s, Jacob Bekenstein and Stephen Hawking made a discovery that still startles physicists: the information content of a black hole—the total amount of data needed to describe everything inside it—is proportional to the *surface area* of its boundary, not its volume. This is deeply counterintuitive. If you want to know how much information is inside a room, you would expect the answer to scale with the room’s volume. But in the presence of gravity, nature says otherwise. The maximum information scales with the surface area.

And if you try to pack more information into a region than its surface allows, the region collapses into a black hole. Nature literally prevents information overload by creating a singularity.

This led to the holographic principle: the complete description of a volume of space can be encoded on its lower-dimensional boundary. In 1997, Juan Maldacena proved this is not an analogy—a gravitational universe in anti-de Sitter spacetime is mathematically identical to a quantum theory living on its boundary (the AdS/CFT correspondence). In 2015, Almheiri, Dong, and Harlow demonstrated something remarkable: the bulk physics in this correspondence is *protected by error-correcting properties* of the boundary encoding. The boundary does not merely describe the interior—it actively protects it against local perturbations. Information encoded on the boundary is robust.

We *conjecture*, following Wheeler, Bekenstein, and Maldacena, that this boundary-dominance structure generalizes beyond black holes and anti-de Sitter spacetimes to any complex system possessing sufficient structure for self-reference. We call this the **Boundary Dominance Principle (BDP)**:

In any system possessing sufficient structure for self-reference, the complete description of the system is encoded on its boundary. The interior is the

reconstruction. And when the boundary is saturated, the system reaches a fundamental limit—a singularity.

This conjecture is illuminated by Lawvere’s fixed-point theorem (1969), which demonstrates that the diagonal arguments underlying Cantor’s theorem, Gödel’s incompleteness, and Turing’s halting problem share a single categorical structure. In each case, the real information lives on the boundary; the interior is derived. **The BDP is not yet a proven result for general systems. It is a hypothesis extended from established black hole physics.** A rigorous holographic correspondence has been proven only for specific gravitational spacetimes (AdS/CFT), and extending it to our actual universe (which has a positive cosmological constant) remains a major open problem. This distinction protects the paper’s scientific integrity: stating what is conjecture and what is proven makes the framework *stronger*, not weaker.

What This Means for Environmental Systems

For environmental systems specifically, the practical consequence of the BDP does not depend on the holographic conjecture being proven in full generality. It follows independently and rigorously from **conservation laws**—conservation of mass, energy, momentum, and chemical species. If the boundary fluxes of an environmental system are measured completely, the interior state is fully determined by these conservation constraints.

For an environmental system, the “boundary” is the set of measurable fluxes at its interfaces: precipitation and evapotranspiration at the atmosphere-land interface, stream discharge and water quality at the watershed outlet, emissions at the facility fence line, groundwater exchange at the subsurface boundary. If these boundaries are measured with sufficient precision, the interior state is constrained by conservation laws. The holographic framing elevates and unifies this insight, but the practical claim stands independently.

You do not need to know what every cubic meter of soil or air is doing. You need to know what is entering and leaving the system at its edges. The interior is the reconstruction.

Part 4: The Bond-Bit Asymmetry

Configuring Matter with Information vs. Force

The most consequential number in this paper is a ratio. It is derived entirely from thermodynamics, and it quantifies the fundamental advantage of working at the information level versus the material level.

The energy required to process one bit of information at the theoretical minimum—the Landauer limit—is:

$$E_{\text{bit}} = k_{\text{B}}T \ln 2 = 2.87 \times 10^{-21} \text{ J (at 300 K)}$$

A critical refinement from Charles Bennett (1973): computation itself can, in principle, be performed *reversibly* at zero energy cost. Only the *erasure* of information—the logically irreversible step—incurs the Landauer cost. This strengthens the information-over-force argument: the thermodynamic floor of information processing is even lower than it first appears. Only forgetting is costly.

The energy required to break one chemical bond (the O-H bond in water):

$$E_{\text{OH}} = 7.71 \times 10^{-19} \text{ J}$$

The ratio at the molecular floor: 268. Knowing is 268 times cheaper than moving, at the single-molecule level. This number is set by the laws of physics—the Landauer limit sits at the thermal fluctuation scale, chemical bond energies sit at the quantum mechanical binding scale—and it will never change. It is as permanent as the speed of light.

At the operational scale of real environmental events, the ratio amplifies dramatically. A 1 kg chemical spill that disperses into soil and groundwater involves rearranging approximately 10^{26} molecular bonds. Preventing the spill through sensor-based prediction and valve closure requires approximately 10^6 – 10^9 bits of information processing.

The Honest Accounting

At the Landauer limit, the operational ratio reaches 10^{19} to 10^{22} , depending on scenario assumptions. This comparison deserves transparent qualification:

On the information side, we are comparing against the *theoretical minimum*—the Landauer limit. Real computers today operate roughly 10^9 above this floor. On the physical side, we are comparing against the *theoretical maximum*—breaking every molecular bond. Real remediation (bioremediation, activated carbon, chemical oxidation) costs far less than total bond breakage.

The honest statement is this: the *fundamental energy scales* of information processing and chemical bond manipulation are separated by the laws of physics, and this separation is permanent. The molecular-floor ratio (268) is rock-solid and unchallengeable. The operational ratio in real scenarios, accounting for current technology and realistic

remediation costs, spans roughly 10^3 to 10^7 . As computational efficiency improves toward the Landauer limit, the practical ratio will continue to grow. The 10^{20} figure represents the *ceiling* set by physics—the maximum possible advantage—not today’s practical advantage.

The fundamental point is unaffected by this qualification: configuring matter with information is, and will always be, vastly cheaper than configuring it with force. The physics guarantees it. The only question is how close technology brings us to the theoretical ceiling.

We formalize this as the Intelligence Leverage Equation:

$$\Lambda = Mc^2 / (I \cdot k_B T \cdot \ln 2)$$

where Λ is the leverage ratio, M is the mass to be configured (Mc^2 representing its rest-mass energy equivalent—not that matter-energy conversion is occurring), I is the information required in bits, k_B is Boltzmann’s constant, and T is the temperature. This equation quantifies the thermodynamic advantage of information over force for any environmental intervention.

Part 5: Protecting and Restoring Nature with Information

From Prevention to Configuration Maintenance

A forest and a wasteland contain the same atoms. Same carbon. Same water. Same nitrogen. The difference is the arrangement. Arrangement is information. And configuring matter with information is vastly cheaper than configuring it with force—by a ratio that grows as technology improves and that is bounded only by the laws of thermodynamics.

This means environmental protection is fundamentally an information problem. Not in the weak sense that “we need better data.” In the strong thermodynamic sense that working at the information level is working at the level where nature herself operates, at costs approaching the thermodynamic floor.

The traditional approach to environmental protection is bulk-first: measure the interior (scatter sensors throughout the system), set static limits (emit no more than X tons per year), and remediate after damage occurs (move contaminated matter by force). This approach is thermodynamically backwards. It attempts to control what happens inside the system without knowing the real-time state of its boundary. And when it fails, the remediation cost

is enormous—because reversing entropy increase requires physical rearrangement at bond-energy cost.

The boundary-first approach inverts this. Measure the boundary—what enters and leaves the system at its interfaces. Reconstruct the interior using physics engines and conservation laws. And steer—not with bulldozers, but with small, precise, information-guided interventions that redirect the system’s own energy toward the desired configuration.

Restoration Through Information

The system already has the energy to reconfigure itself. It just does not know where to send it. Information provides the direction.

A contaminated aquifer can be pumped and treated by brute force—physically extracting millions of gallons, treating them, and reinjecting clean water. Or you can model the groundwater flow in three dimensions, identify the one injection point where a small reagent dose allows the aquifer’s own current to carry the remedy to the plume, and let the water do the work.

A collapsed wetland can be rebuilt with bulldozers. Or you can model the hydrology, remove the one obstruction—a road culvert, a drainage tile—that allows the natural water table to re-establish the wetland configuration on its own. The water does the work. The vegetation follows the water. The ecosystem self-assembles around the restored hydrology. You moved one culvert. Information told you which one. *This works precisely because ecosystems are self-organizing systems—they exhibit emergence, maintaining their own attractors and spontaneously recovering configurations when key constraints are removed. The boundary-first, minimum-intervention approach succeeds because it works with this emergent self-organization rather than against it.*

The pattern is always the same. The system already has the energy to reconfigure itself. It does not know where to send it. That is what information provides. Not force. Direction.

The Write-Read-Steer Loop

The mechanism of informational environmental protection can be stated in three steps:

Write the bit. Observe the system. Place a sensor at the boundary. Measure the flux. A physical interaction occurs, a quantum state is determined, and a bit is inscribed. This is necessary but not sufficient.

Read the bit. Process what was observed. Feed the measurement into a physics model. Reconstruct the interior state from the boundary data. Convert raw data into understanding.

Steer. Act on what was read. If the system is drifting toward a dangerous configuration, direct a minimal physical intervention—close a valve, adjust a discharge, time a treatment—that redirects the system’s own energy toward the desired arrangement.

Skip any step and the loop fails. A sensor nobody reads is a very expensive rock—it writes bits at Tier 4 cost and achieves Tier 1 results. Writing without reading wastes the negentropic investment in the measurement apparatus. Reading without acting wastes the model. The full loop—write, read, steer—is what converts the raw entropic cost of observation into the negentropic benefit of environmental protection.

Part 6: The Three-Layer Architecture

EnviroAI’s architecture was designed from first principles to implement the boundary-first approach. It integrates three layers, each corresponding to a step in the write-read-steer loop:

Layer	Function	Role
Layer 3: Real-Time Data	EPA, USGS, NOAA sensor networks. Live boundary measurements.	WRITE: Direct boundary measurement.
Layer 2: Physics Models	AERMOD, SWAT, physics-informed neural networks. 4D reconstruction.	READ: Interior reconstruction via conservation laws.
Layer 1: Language Intelligence	11M+ environmental documents, agentic RAG, LLM orchestration.	STEER: Interprets the state and directs action.

Read from bottom to top, the architecture follows the logic of boundary reconstruction: Layer 3 measures the boundary, Layer 2 reconstructs the interior, Layer 1 interprets and steers. No single layer can do the job alone. An LLM without physics cannot answer “What PM_{2.5} concentration results 3 km downwind at 2 PM under today’s meteorological conditions?” A physics engine without language cannot interpret what the result means for a specific permit condition. Real-time data without physics or language is just numbers on a screen.

Part 7: The Role of Artificial Intelligence

AI Extends the Pen Across the Entire Page

Where does artificial intelligence fit in the hierarchy of pens? AI is not a new tier. AI is what happens when Tier 4 pens build a tool that closes the write-read-steer loop at a speed and scale that biological pens cannot match.

A human brain processes roughly 10^{16} synaptic operations per second. Remarkable. But it is locked inside one skull, looking at one screen, thinking about one problem at a time. It is a brilliant pen, but it touches one point on the page at a time.

AI makes the loop parallel. The planet has 10^5 major industrial facilities, 10^6 stream segments, 10^7 square kilometers of managed land, and 10^9 humans whose health depends on environmental quality. Closing the loop on all of these simultaneously is beyond any number of humans working manually. Not because the loop is different, but because there are too many loops.

AI is the technology that makes the number of simultaneous loops effectively unlimited.

This is not replacing humans. Humans still do what only Tier 4 pens can do: choose what to observe, decide which questions to ask, determine which configurations of nature are worth maintaining. These are value judgments—choices about what kind of manuscript to write. The human decides what “healthy” means. The AI makes sure it stays that way.

The Three Phases of Environmental AI

Phase 1: AI as labor replacement (now through ~2035). AI takes over the write-read-steer loops that humans currently perform manually—permit analysis, compliance monitoring, incident response, report generation. The billable hour evaporates into infrastructure, not because the function disappears, but because it is performed at an efficiency so much higher than human labor that charging for it makes no economic sense.

Phase 2: AI as entropic shepherd (2035–2055). The three-layer architecture is fully operational at scale. AI does not merely react to violations—it predicts and prevents them. It does not merely monitor the arrangement—it maintains it. Information-guided restoration becomes real at scale. A thermostat for the living world.

Phase 3: AI as background utility (2055+). Environmental protection becomes invisible infrastructure—as invisible and reliable as GPS. The AI reads every boundary of every environmental system on Earth in real time, reconstructs the complete environmental state continuously, and steers continuously at costs approaching the thermodynamic floor. Maximum functional output—a living, thriving planet—at minimum thermodynamic cost.

The Alignment Boundary

As AI systems become more capable, they will begin not just closing loops within human-defined objectives but discovering new loops—new things to observe, new configurations to maintain, new questions to ask. This raises the alignment question: who defines the objectives?

The BDP provides a structural answer. By Lawvere's theorem, any self-referential system—including a sufficiently advanced AI—contains truths about itself that it cannot determine from within. A Tier 4 AI cannot prove, from within, that its own objectives are correct. The complete description of what the AI should value must be encoded on the boundary—the human-defined constraints. This is not a prescriptive answer to *which* humans, with *what* process, should define these boundaries—Lawvere's theorem establishes structural limits on self-reference, not governance procedures—but it does establish that the boundary must exist.

This is the holographic principle applied to AI governance. Humans set the boundary for AI. AI sets the boundary for nature. Nature writes itself. At every level, the same rule applies: define the boundary well, and the interior takes care of itself.

Part 8: Feasibility

No Law of Physics Prevents This

Is there a physically realizable system that can monitor, model, and protect Earth's environmental systems in real time using information processing at costs below the cost of the environmental damage it prevents? We have computed the answer from first principles.

Computational requirement: The total information throughput required for real-time global environmental characterization is approximately 10^{17} – 10^{18} bits/year, with physics modeling requiring approximately 10^{20} – 10^{22} floating-point operations per year. However, real Earth system models at operationally useful resolution (~5–10 km global) require sustained performance of 10^{15} to 10^{18} FLOPS—corresponding to 10^{22} to 10^{25} operations per year—which at current computational efficiency ($\sim 10^{-12}$ J/operation) demands kilowatts to hundreds of kilowatts. This is still remarkably small: the computational energy budget for real-time planetary environmental modeling is comparable to a small data center, not a national grid.

Sensor technology: Sensor costs follow exponential learning curves. Comprehensive US environmental boundary monitoring at regulatory-relevant resolution would cost approximately \$10–50 billion—roughly 1–5% of the annual cost of environmental damage in the US.

Physics models: AERMOD (atmospheric dispersion), SWAT (watershed hydrology), and WRF (weather) are all operational and validated. The models exist.

Fundamental limits: Heisenberg’s uncertainty principle does not constrain macroscopic environmental monitoring. Computational irreducibility (Wolfram) limits exact prediction for some complex systems beyond the Lyapunov horizon (~10–14 days for weather)—some systems cannot be predicted by any means faster than running the system itself. But probabilistic bounds sufficient for regulatory decision-making are achievable, and the write-read-steer loop is specifically designed for this reality: because the future cannot be computed faster than it happens, we sense and steer the boundary in real time rather than attempting to predict from static models.

The barriers are engineering and institutional, not physical: data integration, sensor deployment, and regulatory adaptation. The physics not only permits environmental superintelligence—it thermodynamically favors it.

Part 9: The Efficiency Trajectory

The universe has been optimizing the ratio of functional output to thermodynamic cost for 13.8 billion years. We illustrate this with Generalized Functional Efficiency (GFE), defined as:

$$\text{GFE} = F / (\dot{S} \cdot M)$$

where F is the functional output rate, \dot{S} is the entropy production rate, and M is the mass.

A transparent note on what this metric measures: for systems where functional output equals total power dissipation, GFE reduces to T/M —temperature divided by mass. The 50-order-of-magnitude span in the table below is driven primarily by mass variation (33 orders, from bare semiconductor dies to stars) rather than by differences in computational sophistication. The metric is best understood as an *order-of-magnitude illustration of a real trend*—the universe has produced ever-lighter, ever-more-efficient information processors—not as a precision measurement of functional efficiency:

System	Time	GFE (K/kg)	Log ₁₀ (GFE)
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Big Bang Nucleosynthesis	13.8 Gya	$\sim 10^{-44}$	-44
The Sun	4.6 Gya	$\sim 10^{-26.5}$	-26.5
Photosynthesis	3.8 Gya	$\sim 10^{-15}$	-15
Human Brain	2 Mya	~ 221	2.3
NVIDIA H100 GPU	2023	~ 120	2.1
Neuromorphic Chip	2024	$\sim 10^6$	6
Landauer Limit	Theoretical	$\sim 10^{12}$	~ 12

The trend is real even if the metric is simple: GFE doubling times have compressed from hundreds of millions of years in the biological era to months in the current technological era. The attractor is the Landauer limit—the thermodynamic floor where processing one bit costs the absolute minimum energy that physics allows. Environmental superintelligence is the next point on this curve: a system that maintains Earth’s life-sustaining configurations at a GFE approaching the theoretical maximum.

Conclusion: The Simplest Version of All of This

The entire argument of this paper collapses to five nested statements, each flowing from the last:

- 1. Reality is arrangement.** Same atoms, different structure. Arrangement is information.
- 2. Arrangement builds itself, one bit at a time, according to the principle of least action.** The universe chooses the cheapest path. Always. Dissipative structures channel this process into organized pens—living systems that read and steer the writing.
- 3. The complete description of any arrangement lives on its boundary.** Holographic principle for black holes; conservation laws for everything else.
- 4. Changing arrangement is vastly cheaper with information than with force.** 268 times at the molecular floor. Orders of magnitude more at operational scales. This ratio is set by physics and will never change—and as technology improves, the practical advantage grows toward the theoretical ceiling.
- 5. Therefore: to protect nature, work where she works—at the level of arrangement, using information, guided by the write-read-steer loop.** The only approach consistent with how she builds herself.

The universe is not made of stuff. It is made of arrangement. Arrangement is information.

Artificial intelligence extends this approach to planetary scale—closing the write-read-steer loop across every watershed, every airshed, every ecosystem, simultaneously, continuously, at costs approaching the thermodynamic floor.

Not a single godlike AI, but a distributed network of write-read-steer loops, each working at the information level, each steering the arrangement of matter toward life.

To protect nature, work where she works. At the level of arrangement. At the level of information. One bit at a time.

“Nature operates in the shortest way possible.” — Aristotle

“The best way to protect nature is to emulate her simplicity.” — Jed Anderson

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