PERSPECTIVE

The way we are, function and change: The information, mass and energy theory

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The search for a universal law governing the functioning of life, human society, and Earth is paramount in science. Universal laws, however, are difficult to find in the multifactorial fields of life and human sciences. Gaining insight into the complexities of information driving the form and function, and the energy processes of organisms, ecosystems, and human entities is key to understanding biological and human systems. Here, I propose the IME (information, mass, energy) theory to establish that generally the rate at which information increases with the mass (storage of information) of an organism, ecosystem, or human entity largely surpasses the corresponding increase in mass and required energy. Consequently, larger repositories of information consequently become progressively more powerful and efficient. This exponential increase, however, is not infinite; it reaches a limit marked by the carrying capacity and/or the death of the organism or entity, which finally serves as a mechanism to eliminate negative accumulations of failures or by disturbances that are inversely related to their intensity. This information, mass, and energy (IME) theory that I propose here is key for understanding global change in organisms, ecosystems and human entities as well as biodiversity and habitat carrying capacity, evolution of socio-economic systems and even cosmos development. This IME theory should allow us to model disturbances like drought-related mortality, wildfires, coral bleaching or human socio-economic collapses and predict ecosystem or entity recovery or collapse.

INFORMATION, MATTER, AND ENERGY IN NATURE AND SOCIETY: “THEY WHO ALREADY HAVE MORE GET MORE”

Understanding the principles governing the functioning of living organisms and human entities is crucial for advancing ecological and socio-economic sciences. This understanding requires considering the relationships between information, mass, and energy within the frameworks of information science, ecology, society, and thermodynamics.[1] The essence of life, including humans and their entities such as companies and institutions, resides in information. They are information processors, accumulating information, i.e., the capacity to organize channels and codes of form and function operative inside and outside of the environment.

This information that defines and drives form and function persists and multiplies with time and interactions in organisms and human entities. It does so in a peculiar and effective way that often becomes increasingly larger and more powerful with the accumulation of mass/matter in their structures (storage of information). Information (I) defined by form and function, is proportional ($\propto$) to M^n with M being the mass (storage of information) of a given individual, community, ecosystem or any entity holding information and n an allometric exponent relating I and M generally >1 as stated by Saint Matthew's principle: “they who already have more get more”. History is full of evidence in this line, just as a recent example, archeologists have found that as the Assyrian Empire grew in power, so did the gap between its rich and poor because at least the poor got poorer.[2] This signifies that the information incorporated per unit of mass is subject to a power-law with an exponent n being usually larger than 1 (Figure 1A). Larger storages, organisms and entities may thus have more complex systems for storing and processing information, contributing to adaptive behaviors. For example, the large genetic stores of apes and hominids can generate important somatic differences even if based on very small differences in the respective genotypes. The key issue is the value of n, which may differ depending on the organism or entity but is generally >1, among other reasons, because of the multiplying increase of interactions and complexity (the whole is not explained by just the parts). Determining the precise value of n typically requires empirical data and modeling specific to the system under consideration. The growth of information is thus allometric, as are most things concerning life, supporting Saint Matthews' principle. If an amount of information i and a storage of information (for simplicity from now on: mass) m are added to a system of mass M and information I, we have $I=f(M)\propto M^n$ and $i=f(m)\propto m^n$ such that $(I+i)\propto(M+m)^n$. As $n > 1$, as stated by Saint Matthew's principle, the true value of this i as a bearer of information becomes $(M+m)^n-M^n > i$. Joining or adhering to an existing store of information is therefore more effective than starting anew.[3] One important conclusion is thus that information accumulates more easily and faster where a large core already exists (Figure 1A).

The energy (E) required for the organization and functioning of mass follows a contrasting path to I; the exponent of the power-law relationship with M is usually < 1 (Figure 1A). For example, the incorporation of metabolic scaling laws provides a foundation for understanding the relationship between metabolic rate and body size.[4] Although not always fulfilled and often debated, Kleiber's law,[5] represented by $E\propto M^{0.75}$, suggests that metabolic rate increases at a slower rate than mass as organisms increase in size (and therefore decrease in surface relative to volume).

As a result, the efficiency in accumulating information relative to the energy required in its acquisition, defined by the ratio $I/E\propto M^{n-0.75}$, increases with mass because, as stated, n is generally > 1 (Figure 1A) although not necessarily faster than mass unless n >1.75 (Figure 1A). This expression quantifies the ratio of information to energy, providing a numerical representation of the balance between informational content and energy invested in a system.

INTRODUCING TIME: LIFE AND DEATH, SUCCESSION AND COLLAPSE

The accumulation of mass and information cannot continue indefinitely due to the limited capacity of the environment to sustain a biological system. In other words, resources are not infinite, so one would expect that the closer a system comes to depleting those resources, the slower the growth. That upper limit, which we can identify as the carrying capacity of the system, arises naturally when solving classical differential equations of population growth, progression of a contagious disease or diffusion of technology (e.g., Verhulst equations). A well-known solution to those equations is the equation for logistic growth: $M=\dfrac{K}{1+\left(\dfrac{K}{M_0}-1\right)\cdot e^{-r\cdot t}}$ where K is the constant carrying capacity, t is time, M_0 is the mass at $t=0$, r is the rate of growth, and M is the total mass of the system.

In fact, though, changes toward simplification usually occur discontinuously and appear to be distributed at random. Each of these changes (for example, death, species extinctions, or civilization and company collapses) erases large stores of information. The curves for I and I/E, therefore, end more abruptly due to some disturbance, so we can modify the previous sigmoid function to introduce a factor that causes a rapid decline in the values, the disturbance factor, that controls the endings of the curves.

In practice, systems are affected by transient disturbances that reduce directly their total current mass M temporarily and diminish indirectly the carrying capacity K of the system through, e.g., resource depletion or habitat degradation. Such effects may occur relatively quickly, leading to a drop in system mass until the disturbance ends and the system begins to recover or disappears (Figure 1B). The aftermath of such a disturbance may measurably affect energy and information. Nevertheless, for the sake of simplicity we will model the disturbance as a temporal pulse-like factor (e.g., infection by mountain pine beetle outbreaks, tsunami or hurricane) affecting total mass M only. Subsequently, we will assume it to follow a Gaussian curve: $D=Q\cdot e^{-\frac{(t-t_0)^2}{2\cdot\sigma^2}}$.

In our implementation, D affects our system as a coefficient multiplying M. Parameter σ in turn determines the width of the disturbance, i.e., its duration,

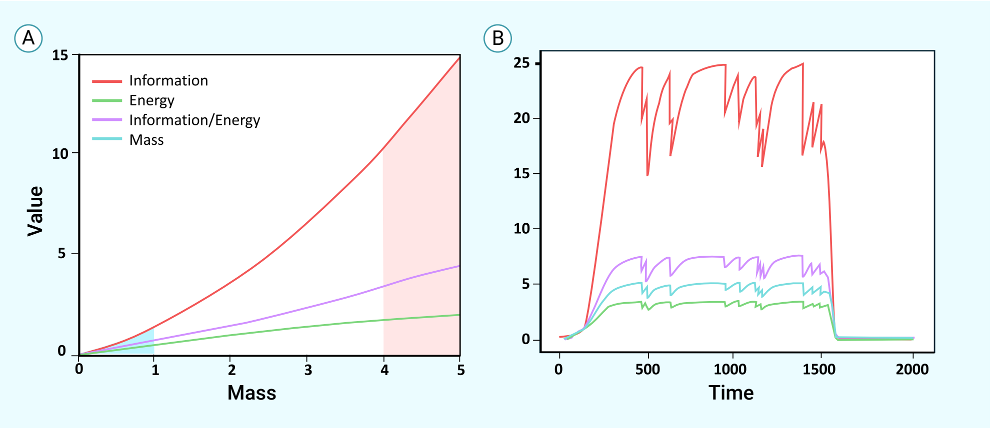

Figure 1. Information (I), energy (E), and efficiency (I/E) as a function of mass (M) (A) and their trends with time (unitless) (B) (A) Information equation $I=M^n$ and energy equation: $E=M^{0.75}$; example for n = 2. (B) Reaching a limit and adding disturbances of different intensity with a final one that drives to death/extinction/collapse. For illustration purposes, the constants of proportionality are always 1. Notice in (A) that the same mass joining or adhering to an existing larger mass (store of information) is more effective (red mesh) than starting anew (blue mesh)

and constant Q $(0 < Q < 1)$ allows us to determine the strength of the disturbance. When $t = t_0$ (i.e., when the disturbance is at its maximum), disturbance $D = Q$ and then if Q = 1 the system disappears. A possible analytical implementation of the disturbance affecting system mass is then: $M = \frac{K}{1+\left(\frac{K}{M_0}-1\right)\cdot e^{-r\cdot t}}\cdot(1-D)$.

For simplicity, we could consider a system with a mass M that grows steadily over time. This consistent increase in M continues until a disturbance occurs (as mentioned earlier), which causes a sudden drop in M. This drop leads to a corresponding decrease in I and E, until the system's inherent dynamics allows M and I to recover or collapse (Figure 1B). As a result, the expression for I at time t is given as follows:

$$I_t = \alpha M^n$$

$$I_t = \alpha\left[\frac{K}{1+\left(\frac{K}{M_0}-1\right)e^{-rt}}\left(1-Qe^{-\frac{(t-t_0)^2}{2\sigma^2}}\right)\right]^n$$

α being a proportionality constant characteristic of the kind of organism or entity.

Abrupt decreases in mass and information associated with disturbances or collapses occur with a frequency inverse to their intensity[6,7] (Figure 1B).

IRREVERSIBILITY

This information, mass and energy (IME) theory thus deals with growth, disturbance and recovery of organisms, communities, ecosystems and human entities but we cannot neglect that information storage in all these processes is strongly irreversible, which in fact becomes a reason for death and birth, succession, and collapse. The process of acquiring information, both on an individual level between growth and death and at the ecosystem level between succession and catastrophic destruction, cannot be reversed. Extracting individual threads or elements acquired successively over time and returning to youth is impossible. If it were possible, it would result in the loss of the multiplicative property of the accumulation of information. The most efficient and cheapest solution, because the mechanism of genetic copying and reproduction of organisms works so well and is so thermodynamically cheap, is to include death as a normal event in the program, thus allowing selection and the Darwinian evolution of living organisms and human entities, or perhaps even big bangs of the universes, as Margalef (1997)[3] wondered.

An example of the irreversibility of information storage can be seen in the process of ecological succession following a disturbance, such as a forest fire. After a fire clears a landscape, the initial information encoded in the structure and species composition of the original forest is lost. While new growth emerges and a succession of species repopulates the area, the specific arrangements, age structures, and relationships of the original ecosystem cannot be restored. For instance, the intricate relationships between mycorrhizal fungi and tree roots that existed prior to the fire will never exactly replicate, leading to a different community structure that may harbor new species or altered interactions. This loss of information contributes to a new ecological state, showing that each disturbance not only transforms the ecosystem but also irreversibly alters the available information that governs its future trajectory.

CASE STUDIES IN GLOBAL CHANGE BIOLOGY, HUMAN ENTITIES AND COSMOLOGY

Understanding the principles of this IME theory is particularly relevant in the context of global change biology, human sciences and cosmology. The IME theory provides a framework for understanding the interplay between information, mass, and energy in both biological and human systems, offering a basis for several targeted case studies. There are multiple examples regarding ecosystem disturbance and resilience, biodiversity and carrying capacity, or evolution of socio-economic systems and cosmos.

Forest ecosystems store vast amounts of information in their biodiversity, structure and functioning. Disturbances such as wildfires cause abrupt decreases in mass (biomass) and information (biodiversity and functioning). This IME theory can help predict the impact of such events and the subsequent recovery period. For example, the increased frequency and intensity of wildfires in the Amazon due to climate change and deforestation can be modeled to understand how resilience is affected by focusing on how pre-existing information structures influence post-fire regeneration in various fire-prone habitats, thereby providing insights into ecosystem resilience through IME interactions. Coral reefs are another example where mass (coral biomass) and information (species diversity and functioning) are crucial. Ocean acidification and warming cause bleaching events, analogous to the disturbances modeled by the Gaussian curve, leading to significant losses in mass and information. Predicting the possible recovery or the collapse of these ecosystems through this IME approach can inform conservation efforts.

The IME theory has significant implications for human entities and socio-economic systems. For instance, increasing urbanization often increases mass (human population and infrastructure) and information (economic, cultural, and technological), frequently at the expense of natural ecosystems. A thorough understanding of the balance between growth and carrying capacity within urban systems can guide sustainable development practices to ensure liveability and resilience in cities. In urban socio-economic systems experiencing downturns, opportunities arise to examine how information structures within social networks influence community recovery and resilience.

In agricultural systems, knowledge exchange plays a crucial role in enhancing resilience to climate variability and pest outbreaks. By assessing biomass, resource allocation, and information-sharing practices among farmers, case studies can illustrate the importance of effective information management in sustaining and recovering from agricultural shocks.

Similarly, large enterprises often increase mass (market share and production) and information (industry knowledge and technological capabilities) at the expense of smaller firms. Understanding the balance of growth and carrying capacity in corporate systems can inform sustainable business practices that promote competitiveness and resilience. Large companies accumulate significant information through data management and operational efficiencies, while disruptions—such as economic recessions or regulatory changes—can lead to sudden drops in economic output and organizational knowledge. The Gaussian disturbance model can predict the consequences of these disruptions and the subsequent recovery phases. Analyzing increased market disruptions due to geopolitical tensions and technological advancements can elucidate their effects on resilience and adaptability.

Comparing large corporations, like Amazon, with small local retailers reveals differing impacts of information structures on economic dynamics. Amazon's extensive data infrastructure and logistical networks enhance operational efficiency and adaptability, facilitating expansive growth. In contrast, smaller retailers, constrained by limited information systems, may struggle with growth yet capitalize on personalized service and community engagement opportunities often overlooked by larger entities. This comparison highlights how varying structural complexity and functional integration affect economic resilience and scalability.

The IME theory can also be applied in a cosmological context to investigate how information —inherent in the structure and function of cosmic entities—influences the universe's evolution. By studying large-scale cosmic structures such as galaxies, researchers can analyze mass distribution and energy dynamics to understand how information is encoded through cosmic patterns, including the cosmic microwave background. Cosmological simulations can model structure formation, displaying how increased mass and complexity yield intricate information structures impacting energy processes like star formation and black hole dynamics. This exploration may reveal universal limits to these information-bearing systems and consider scenarios such as entropy, heat death, or the big rip, offering insights into how cosmic information structures influence the universe's fate.

These possible case studies demonstrate the broad applicability of IME theory, enhancing our comprehension of the structural and functional roles of information in promoting resistance (vulnerability), resilience, and efficiency across diverse systems —ranging from local businesses, ecosystems, and agricultural landscapes to complex urban networks, communities, and even the cosmos. This framework shapes the dynamics of these systems, yielding valuable insights for both theoretical exploration and practical implementation.

ASSUMPTIONS AND MODEL TESTING

The model and approach here presented regarding information, mass and energy includes several assumptions. For example, the Gaussian disturbance model assumes that disturbances have a pulse-like impact, with intensity and duration characterized by specific parameters. This simplification helps model complex real-world events like wildfires, hurricanes, or disease outbreaks; and the model assumes that larger systems (organisms, ecosystems) are more energy-efficient, following metabolic scaling laws.

Testing the model with empirical data will be essential to validate the predictions of IME theory and refine its parameters. This will require data on mass, information, and energy use from various ecosystems and socio-economic systems. It includes monitoring changes over time, especially in response to disturbances, and using statistical methods to estimate the model parameters (n, K, Q, σ, and α) from the collected data. This will help tailor the model to specific systems and improve its accuracy. Finally, it is crucial to continuously refine the model based on discrepancies between predictions and observations. Incorporating feedback from empirical studies will thus enhance the robustness and applicability of this IME theory.

COMPARISON WITH OTHER GENERAL THEORIES

The information-energy-mass theory differs from other relevant frameworks such as Landauer's principle, network theory or allometric scaling theory.

The Landauer's principle states that the minimum energy needed to erase one bit of information is proportional to the temperature at which the system is operating, thus linking information processing to thermodynamics.[8] Landauer's principle thus primarily addresses the thermodynamic costs of information processing. In contrast, the IME theory suggests a scaling relationship between information and mass, indicating that larger systems not only require more energy but also offer enhanced capabilities for information storage and processing, potentially leading to exponential growth in information efficiency.

The network theory studies the relationships and interactions in complex systems, often illustrated through models like preferential attachment, which explain how certain nodes gain connections more rapidly, resulting in power-law distributions.[9] Like IME, this theory emphasizes growth, interconnectivity, and the accumulation of advantages, but network theory lacks a direct focus on mass or energy. The IME theory supplements this by proposing that larger systems (information stores) possess superior information capabilities alongside structural advantages, thereby linking energy and mass characteristics to emergent patterns in complex networks.

The allometric scaling theory describes how biological characteristics, such as metabolism and growth, scale with body mass, typically exhibiting power-law relationships.[4] This theory specifically concentrates on biological systems, whereas the IME theory applies to both natural and artificial systems, positing that mass significantly influences information storage and processing. Allometric scaling theory predicts metabolic rates will rise with mass, but the IME theory further explores how mass affects biological information and the potential limits of energy efficiency in non-biological contexts.

In summary, while each of these theories provides critical insights into the dynamics between information, energy, and mass, they differ fundamentally in implications, focus, and predictive power. The IME theory stands out by offering a holistic synthesis of these concepts, paving the way for interdisciplinary applications that enhance our understanding of scaling relationships across diverse fields, including physics, biology, social and economic sciences and even cosmology.

CONCLUSION AND FINAL REMARKS

Understanding the intricate balance between information, mass, and energy is fundamental to comprehending the dynamics of biological and human systems. The principles here outlined provide a framework, the IME theory, for exploring these relationships and their implications. The interplay between information accumulation and energy requirements, constrained by environmental limits and punctuated by disturbances, shapes the evolution and functioning of organisms and human entities. The IME's theory integrates the five laws of life[1] by determining the relationships among information, mass and energy through time and after disturbances. This way the IME' s framework provides a comprehensive lens for understanding biological and human systems, but uncertainties exist in quantifying information processes, predicting the responses of organisms, ecosystems, and entities, and generalizing principles across diverse taxa and entities and consequent diverse metabolic, cognitive, ecological, or organizational characteristics. Addressing these uncertainties requires ongoing research and collaboration across disciplines. These considerations regarding information, mass, and energy extend beyond biology and ecology; they are also relevant to sociology, economics, physics, cosmology, and all branches of science. The IME holistic approach fosters interdisciplinary collaboration and enhances our comprehension of complex phenomena in both natural and social sciences.

Beyond theoretical advances, these considerations could ultimately have practical implications. Insights gained can contribute to the development of biologically inspired technologies and enhance our understanding of ecological and socio-economic systems, potentially informing efforts of conservation and sustainability and providing more-informed approaches to social and economic challenges.

Future research should focus on refining these models with empirical data, exploring the specific values of exponents in different contexts, and further integrating the effects of disturbances. This would enhance our ability to predict and manage the behavior of complex systems, contributing to sustainable development and resilience in the face of current global change.

REFERENCES

1. Peñuelas, J. and Baldocchi, D. (2019). Life and the five biological laws. Lessons for global change models and sustainability. Ecol. Complex. **38**: 11–14. DOI: 10.1016/j.ecocom.2019.02.001.
2. Creamer, PM. (2024). Inequalities in wealth distribution within Imperial Assyrian graves. Antiquity **98**: 920–935. DOI: 10.15184/aqy.2024.81.
3. Margalef, R. (1997). Our biosphere. O. Kinne (ed.), Excellence in Ecology, 10. (International Ecology Institute), pp: 176.
4. West, G. B., Brown, J. H., and Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. Science **276**: 122–126. DOI: 10.1126/science.276.5309.122.
5. Kleiber, M. (1932). Body size and metabolism. Hilgardia **6**: 315–353. DOI: 10.3733/hilg.v06n11p315.
6. Pickett, S.T.A. and White, P.S. (1985). The Ecology of natural disturbance and patch dynamics (Academic Press).
7. Jentsch, A. and White, P. (2019) A theory of pulse dynamics and disturbance in ecology. Ecology **100**: e02734. DOI: 10.1002/ecy.2734.
8. Landauer, R. (1961). Irreversibility and heat generation in the computing process. IBM J.Res.Dev. **5**: 183–191. DOI: 10.1147/rd.53.0183.
9. Barabási, A.-L. and Albert, R. (1999). Emergence of scaling in random networks. Science **286**: 509–512. DOI: 10.1126/science.286.5439.50.

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DECLARATION OF INTERESTS

The author declares no competing interests.