

Investigating the Link between Energy, Matter, and Information: The $E=mc^2$ and Landauer Principle

Boris Menin

Department Mechanical & Refrigeration Expert, Beer-Sheva, Israel

Abstract Albert Einstein's famous equation $E=mc^2$, which explains the source of stellar energy and the development of nuclear weapons, is not only practically significant but also fundamental to our understanding of the universe. Recent research shows that information, which is considered a new form of physical matter, is closely linked to this equation, making it an essential part of the physical world. This article discusses the relationship between $E=mc^2$ and Landauer's principle, which states that erasing information requires a minimum amount of energy, emphasizing the role of information in the physical universe. By exploring the connection between these equations, the article presents two methods for integration, highlighting their potential for new discoveries in physics.

Keywords Earth's volume, Einstein, Energy-Mass Equivalence, Information Theory, Information-Energy Equivalence, Landauer, Storage Density

1. Introduction

The formula $E=mc^2$ is one of the most famous equations in the history of physics, and it has played a pivotal role in shaping our understanding of nature. The equation was first proposed by Albert Einstein in 1905 as part of his special theory of relativity [1]. In recent years, scientists have explored the idea that information itself can be considered a new form of physical matter, and the $E=mc^2$ equation has played a crucial role in this development.

This concept of information as a physical entity is since information has a physical manifestation in the universe and requires energy to process, store, and transmit. The connection between energy and information is not new, as the concept of information entropy, first introduced by Claude Shannon in 1948 [2], provides a framework for understanding the physical properties of information.

It has been shown that the amount of information that can be stored in a physical system is limited by a fundamental bound called the Bekenstein limit [3]. This limitation sets an upper limit on the amount of information that can be contained within a given region of space, based on the mass and energy of that region. The Landauer principle [4], which states that erasing a bit of information requires a minimum amount of energy, is also related to this concept.

The relationship between these ideas suggests that information is a fundamental part of the physical universe,

and that understanding the physical properties of information is crucial for a complete understanding of the nature of the universe. However, it is important to note that the Landauer principle has been heavily criticized by J.D. Norton [5]. Nonetheless, the Landauer principle has been defended in [6], and the discussion is far from over.

While some may criticize the approach that links Einstein's formula to information without a deeper explanation, it is important to note that the significance of information in storage, transmission, and processing was not widely recognized until relatively recently. In the last decade, numerous studies investigating the relationship between $E=mc^2$ and information have been published [7-16], each contributing significantly to our understanding of the nature of information and its role in physics. However, it is important to note that some of the articles have certain limitations that should be considered. For example, Verlinde's review on holography and emergent gravity [11] focused on theoretical frameworks for understanding gravity, but it may be limited in its practical applications. Yamamoto and Hayashi's article [12] used technical language and dealt with complex concepts that may be difficult for many readers to fully understand. Merdji and Zubairy's article [13] had limited scope and may not apply to more general systems. Gemmer, Mahler, and Winter's book [15] provided a comprehensive overview of the field but may be too technical for a general audience. Lastly, while Marvian and Spekkens' article [16] presents interesting theoretical results, it may have limited practical applications and is based on certain assumptions.

One article by E. Bormashenko [17] deserves special mention. The author argues that the erasure of a bit of

* Corresponding author:

meninbm@gmail.com (Boris Menin)

Received: Jun. 1, 2023; Accepted: Jun. 10, 2023; Published: Jun. 12, 2023

Published online at <http://journal.sapub.org/ajcam>

information necessarily leads to an increase in entropy and suggests that this principle can act as a steppingstone towards unifying various branches of physics. However, one of the possible contradictory statements of this article is the declaration of the identity of the nature of Einstein's laws and Landauer's principle, namely the identities of information-energy equivalence and mass-energy equivalence. This statement is doubtful because the energy required to erase one bit of information, which is proportional to temperature (kT), is not equivalent to the energy associated with mass.

In this article, we explore the relationship between the $E=mc^2$ equation and the Landauer principle, and how these concepts relate to the physical properties of information. To avoid the potential backlash associated with insufficient explanation of the underlying physical justifications for the proposed formulas, it is important to thoroughly reason through and substantiate any claims made. While some may criticize the approach that links Einstein's formula to information without a deeper explanation, it is important to note that the importance of information in storage, transmission, and processing was not widely understood or appreciated until relatively recently.

This task is challenging and requires a deep understanding of both formulas and their underlying principles. The upcoming chapter will explore the details of this task and the potential implications of a unified framework for our understanding of the physical universe.

2. Unifying Energy-Mass and Information-Energy Equivalences

The proposed research examines the connections between Einstein's energy-mass equivalence and Landauer's information-energy equivalence using dimensional analysis. This method provides insights into the relationships between physical quantities and underlying principles, allowing for accurate equation verification and error detection.

To make scientific progress, it is essential to analyze new ideas rigorously, considering complex phenomena. Oversimplification and neglecting important aspects hinder understanding and impede research. Utilizing up-to-date scientific data and validated findings from reputable journals is crucial for validating calculations and hypotheses. Rigor and precision are necessary to ensure the integrity and credibility of scientific advancements in this field.

2.1. The First Proposal

In this study, we aim to integrate the Einstein formula (1) and the Landauer formula (2) by utilizing the dimensional analysis method, while considering any of its potential drawbacks. By conducting a thorough analysis of the physical implications of the formula and using dimensional analysis to explore their relationships, we can achieve a more profound understanding of the interdependence between energy, mass, and information:

$$E_m = m \cdot c^2, \quad (1)$$

$$E_I = k_b \cdot T \cdot \ln 2, \quad (2)$$

where E_m is the energy of the body [$M^1 \cdot L^2 \cdot T^{-2}$], m is the mass of the body [M], c is the speed of light [$M \cdot T^{-1}$], E_I is minimum possible amount of energy required to erase one bit of information [$M^1 \cdot L^2 \cdot T^{-2}$], k_b is Boltzmann constant [$M \cdot L^2 \cdot T^{-2} \cdot K^{-1}$], T is temperature of the heat sink [K]. For all the listed variables, their dimensions are presented in the form of base quantities of the SI (International system of units) [18].

We introduce the Einstein formula as:

$$E = m \cdot c^2 = V \cdot d \cdot c^2, \quad (3)$$

or

$$d = E/(V \cdot c^2) = d_m + d_I, \quad (4)$$

This formula relates the specific density of a body to its volume, V , and the two components of specific density d : d_m , representing the density due to energy-mass equivalence, and d_I , representing the density due to information-energy equivalence. Understanding the interplay between energy, mass, and information is crucial, and using the concept of specific density can provide a comprehensive analysis. However, actual data is necessary to test the relationship between d_m and d_I .

The Earth's average density is a significant topic in geophysics. Depending on the model used, the Earth's average density, d_E , ranges from 4,500 kg/m^3 to 5,515 kg/m^3 [19], which is crucial in understanding the Earth's internal structure. By using this data, we can further investigate the relationship between energy, mass, and information. For our analysis, we select the Earth's average density d_E as our reference value:

$$d_{Em} = 5,515 \text{ (kg/m}^3\text{)} \quad (5)$$

This density is higher than most common rocks, suggesting that the Earth's interior is composed of denser materials, such as iron and nickel.

While Einstein's formula only considers mass in terms of energy, some scientists have explored the concept of information having a connection to mass. In article [7] Lloyd calculated the total number of bits stored on Earth to be approximately 10^{21} , with each bit of information requiring a minimum amount of energy to store it. This led Lloyd to suggest that there is an information mass included in the Earth's sphere m_{IE} :

$$m_{IE} = 10^{-8} \text{ (kg)} \quad (6)$$

To determine the specific density of information in the Earth's sphere, we need to know the Earth's volume. Williams [20] published a precise estimate of the Earth's volume, V_E , which he calculated to be approximately $V_E = 1.08 \cdot 10^{21} \text{ m}^3$.

In this case, the formula for d_{IE} , the specific density caused by information, is given by:

$$\begin{aligned} d_{IE} &= m_{IE} / v_E = 10^{-8} / 1.08 \cdot 10^{21} \\ &= 0.92 \cdot 10^{-29} \text{ (kg/m}^3\text{)} \end{aligned} \quad (7)$$

The total specific density of the Earth d_E is then given by the sum of d_{Em} , the specific density of ordinary matter, and d_{IE} , as follows:

$$d_E = d_{Em} + d_{IE} = 5,515 + 0.92 \cdot 10^{-29} \text{ (kg/ m}^3\text{)} \quad (8)$$

In the present era, the specific density and mass of an object, such as Earth's sphere, are mainly determined by Einstein's Energy-Mass Equivalence, while the Landauer principle has an insignificant influence. However, the exponential growth of digital information production may change this balance. Vopson's article [21] discusses how the growth of digital information production will eventually surpass the number of atoms on Earth, consuming a significant portion of the planet's power capacity. In addition, Vopson notes [22] that the mass-energy-information equivalence principle proposed by Landauer [23] has yet to be experimentally verified. If true, it could be expected that most of the planet's mass would eventually be composed of bits of digital information. This raises important questions about the potential impacts on society and the environment that must be carefully considered. According to Vopson's calculations, if the annual growth rate of digital content creation continues at 50%, humanity would produce a digital information mass equivalent to 10% of the Earth's mass (the Earth's current mass M_E is $5.97 \cdot 10^{24}$ kg [24]) in approximately 67 years. Therefore, scientists may need to update Einstein's formula (9) soon:

$$E = m \cdot c^2 = V \cdot (d_m + d_i) / c^2 \quad (9)$$

While the behavior of information has been the subject of extensive research, it remains a topic of great interest and intrigue, with numerous unanswered questions - especially when it comes to its behavior at speeds approaching that of light. This area of study continues to be highly thought-provoking, inspiring ongoing scientific inquiry and exploration.

2.2. The Second Proposal

Information overload is becoming an increasingly significant problem due to the growing amount of data being produced and stored. This chapter aims to provide a qualitative analysis of the challenges posed by this issue and explore potential solutions. The proposed formula combines Einstein's formula for energy and mass equivalence with Landauer's formula for information and energy equivalence. By equating the energy terms and solving for mass in terms of temperature and information, we get:

$$E = m \cdot c^2 + k_b \cdot T \cdot \ln 2 \quad (10)$$

The inclusion of the $k_b \cdot T$ term in this equation is related to Landauer's principle, which states that the erasure of one bit of information in a computer requires an energy cost proportional to temperature. This means that there is a potential link between mass, temperature, and information, with each term possessing the same dimensions, as required by dimensional analysis. However, it is crucial to establish a plausible physical justification to support the equation.

Equation (10) can be transformed as follows:

$$E_{mi} = V_m \cdot d_m \cdot c^2 + V_m \cdot Q_{be} \cdot k_b \cdot T \cdot \ln 2 \quad (11)$$

In this context, E_{mi} refers to the energy of a given body, comprising mass-energy equivalence and information-energy equivalence. V_m denotes the volume of the body, and d_m signifies the specific density. Finally, Q_{be} represents the quantity of information (in bits/m³) contained within the material object.

The scientific community has debated whether information can be assigned a mass value. The traditional belief is that information is an abstract concept and cannot be assigned a mass value in kilograms because it is not a physical object. However, according to Landauer's principle [23], the energy required to erase one bit of information is proportional to temperature (kT), but this energy is not equivalent to a mass value. At the same time, some researchers [7,22] argue that it is possible to assign a mass value to information in kilograms. They view information as a physical object with mass. When considering the amount of information stored in a physical system such as a hard drive, the information itself contributes to the overall mass of the system, in addition to the mass of its individual components like platters, read/write heads, and electronics. While both views have their merits, the debate highlights the complexity of understanding the nature of information and its relationship with physical reality.

To examine the formula (11), it is essential to consider the latest findings in the computer industry. A scientific publication [25] describes a new technique for storing digital information using individual atoms. The authors calculated that their technique could theoretically store up to 1.25 petabits per cubic centimeter ($1.25 \cdot 10^{21}$ bits/m³) and mentioned an areal density of 502 terabits per square inch ($7.7 \cdot 10^{17}$ bits/m²).

Commercial hard disk drives have continued to increase in storage density. Seagate Technology achieved a storage density of about 2.6 terabits per square inch ($d_b = 4 \cdot 10^{15}$ bits/m²) with a demonstration of a 20-terabyte hard drive that uses heat-assisted magnetic recording (HAMR) technology [26]. This achievement has practical implications for estimating the amount of information (bits) in 1 m³, Q_{be} , in a real-world material environment. For instance, considering a typical hard disk drive (HDD) with a thickness of $h_{hd} = 1.028$ cm = $1.028 \cdot 10^{-2}$ m. Then we can calculate an amount of information (bits/m³) included in HDD, Q_{be} :

$$Q_{be} = d_b / h_{hd} = (4 \cdot 10^{15}) / (1.028 \cdot 10^{-2}) \quad (12) \\ \approx 3.9 \cdot 10^{17} \text{ (bits/m}^3\text{)}$$

Therefore, this calculation shows that there are about $3.9 \cdot 10^{17}$ bits/m³ included in the material object, and the conclusions seem to be accurate based on the density achieved by Seagate's hard disk drive.

If a disk diameter D_{hd} equals 3.5 inches (8.89 cm), the volume of the disk V_{hd} can be calculated:

$$V_{hd} = \pi \cdot (D_{hd}/2)^2 \cdot h_{hd} \approx 64 \text{ cm}^3 = 6.4 \cdot 10^{-5} \text{ m}^3 \quad (13)$$

Additionally, it must be mentioned that although the mass of an HDD can vary depending on factors such as its capacity

and number of platters, we can assume an average mass m_{hd} of approximately 0.11 kg for this analysis. Consequently, the density of the disk d_{hd} can be determined as:

$$\begin{aligned} d_{hd} &= m_{hd} / V_{hd} = 0.11 / 6.4 \cdot 10^{-5} \\ &\approx 1.7 \cdot 10^3 \text{ (kg/m}^3\text{)} \end{aligned} \quad (14)$$

By incorporating equations (12), (13) and (14), we can further develop Equation (11) for the material object - Seagate's hard disk drive:

$$\begin{aligned} E_{hd} &= d_{hd} \cdot V_{hd} \cdot c^2 + V_{hd} \cdot Q_{be} \cdot k_b \cdot T \cdot \ln 2 \\ &= 1.7 \cdot 10^3 \cdot 6.4 \cdot 10^{-5} \cdot 9 \cdot 10^{16} \\ &+ 6.4 \cdot 10^{-5} \cdot 3.9 \cdot 10^{17} \cdot 9.569926 \cdot 10^{-24} \cdot 300 \\ &\approx 9.8 \cdot 10^{15} + 7.2 \cdot 10^{-8} \end{aligned} \quad (15)$$

where $c = 299,792,458 \text{ m}\cdot\text{s}^{-1}$, $c^2 = 9 \cdot 10^{16} \text{ m}^2 \cdot \text{s}^{-2}$, $k_b \cdot \ln 2 = 9.569926 \cdot 10^{-24} \text{ kg}\cdot\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$, $T = 300 \text{ }^0\text{K}$.

Dimensions of the Equation (15) by two parts are equal:

$$\begin{aligned} &[\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-2}] \\ &= [\text{m}^3 \cdot \text{bit} \cdot \text{m}^{-3}] \cdot [\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}] \cdot [\text{K}^1] \cdot [\text{bit}^{-1}] \end{aligned}$$

The equation (15) highlights a significant difference between its two components, with the first part being substantially larger than the second. However, it is essential to acknowledge that both equations (9) and (15) are theoretical and require empirical verification to establish their accuracy. Furthermore, a thorough understanding of each term's physical significance is crucial to apply them effectively. It is noteworthy that, in the present era, the mass of information is considered negligible in comparison to the mass connected to energy. Although these formulas demonstrate potential in various fields such as thermodynamics, information theory, and quantum mechanics, further research is necessary to fully comprehend their implications and limitations. Only then can we harness their potential and utilize them in practical applications.

3. Discussion

The energy-mass equivalence formula, $E=mc^2$, and the information-energy equivalence formula, $\Delta E=k_b T \cdot \ln 2$, have significant implications for modern physics and information theory. These equations suggest a potential connection between energy, mass, and information, which has been explored in recent research. This connection implies that information has mass, and this has been experimentally confirmed in the fields of quantum mechanics and thermodynamics.

The concept that information has mass suggests that the universe is richer in information than previously thought since the energy required to store information is proportional to its mass. This relationship has practical implications for future technologies, particularly in the development of quantum computing. A better understanding of how information is stored and processed at the quantum level may lead to more efficient and effective quantum computing systems.

However, some scientists remain skeptical of the idea that the energy associated with erasing information is equivalent to a mass value since energy and mass are distinct concepts in physics. Despite this skepticism, the concept of information as a physical quantity is a fascinating area of research that could transform our understanding of physics and information theory, and open new possibilities for technological advancement [27,28].

Quantitative calculations suggest that the "bit" concept can be applied to the technology used to store and process bits in digital devices, potentially affecting their performance. The connection between energy, mass, temperature, and information has practical implications for future technologies and could revolutionize the field of information technology.

In summary, the concept that information has mass provides new insights into the fundamental nature of the universe and could lead to exciting breakthroughs in information technology. The relationship between energy, mass, and information is a fascinating topic that has generated considerable interest and discussion in the scientific community. Further research in this area could have far-reaching implications for our understanding of physics and the development of new technologies.

4. Conclusions

The energy-mass equivalence formula and the information-energy equivalence formula proposed by Einstein and Landauer have had a significant impact on modern physics and information theory. Recent research has suggested a possible connection between these two equations based on the thermodynamic properties of information, which implies that information possesses mass.

This relationship has potential implications for our understanding of the universe and the development of future technologies, such as quantum computing. The Landauer limit may also be a fundamental limit on the amount of information that can be processed by any physical system.

Although this idea is still being explored and refined, it has the potential to transform our understanding of physics and information theory, leading to exciting breakthroughs in the field of information technology. Further research in this area could shed new light on a wide range of physical phenomena and provide new insights into the fundamental nature of the universe.

ACKNOWLEDGEMENTS

Grateful for Prof. Mark Burgin's invaluable assistance in editing and preparing my article for publication. His expertise in mathematics, computer science, and information sciences has greatly contributed to its quality. May he rest in peace.

REFERENCES

- [1] Einstein, A. 1905. Does the inertia of a body depend upon its energy-content?, *Annalen der Physik*, 17(1): 891-921. <https://sci-hub.se/10.1002/andp.19053221004>.
- [2] Shannon, C.E. 1948. A mathematical theory of communication, *Bell System Technical Journal*, 27(3): 379-423. <https://sci-hub.se/10.1002/j.1538-7305.1948.tb01338.x>.
- [3] Bekenstein, J.D. 1973. Black holes and entropy, *Physical Review D*, 7(8): 2333-2346. <https://sci-hub.se/10.1103/PhysRevD.7.2333>.
- [4] Landauer, R. 1961. Irreversibility and heat generation in the computing process, *IBM J. Res. Dev.*, 5(3): 183-191.
- [5] Norton, J.D. 2005. Eaters of the lotus: Landauer's principle and the return of Maxwell's demon, *Stud. Hist. Philos. sci. B.*, 36, 375-411. Doi: 10.1016/j.shpsb.2004.12.002.
- [6] Ladyma, J., and Robertson, K. 2013. Landauer defended: Reply to Norton, *Stud. Hist. Philos. sci. B.*, 44, 263-271. Doi: 10.1016/j.shpsb.2013.02.005.
- [7] Lloyd, S. 202. Computational capacity of the universe, *Physical Review Letters*, 88(23), 237901. <https://sci-hub.se/10.1103/PhysRevLett.88.237901>.
- [8] Bousso, R. 2002. The holographic principle, *Reviews of Modern Physics*, 74(3): 825-874. <https://sci-hub.se/10.1103/RevModPhys.74.825>.
- [9] Adami, C. 2015. Information-theoretic considerations concerning the origin of life, *Origins of Life and Evolution of Biospheres*, 45(3): 239-244. Doi: 10.1007/s11084-015-9439-0.
- [10] Abbott, B.P., et al. 2016. Observation of gravitational waves from a binary black hole merger, *Physical Review Letters*, 116, 061102: 1-16. <https://sci-hub.se/10.1103/PhysRevLett.116.061102>.
- [11] Verlinde, E. 2017. Emergent gravity and the dark universe, *SciPost Phys.*, 2(016): 1-41. <https://scipost.org/SciPostPhys.2.3.016/pdf>.
- [12] Yamamoto, N., and Hayashi, M. 2018. A new perspective on thermodynamics: Statistical mechanics and information geometry, *Reports on Progress in Physics*, 81(6), 066001.
- [13] Merdji, H., and Zubairy, M.S. 2019. Thermodynamics with continuous information flow, *Physical Review E*, 99(2), 022139.
- [14] Kosloff, R. 2013. Quantum thermodynamics: A dynamical viewpoint, *Reports on Progress in Physics*, 15(6): 2100-2128; <https://doi.org/10.3390/e15062100>.
- [15] Gemmer, J., Mahler, G., and Winter, A. (Eds.) 2019. *Quantum Thermodynamics: From Fundamentals to Applications*, Springer International Publishing. Cham, Switzerland.
- [16] Marvian, I., and Spekkens, R.W. 2020. Quantum-information-theoretic limits on thermodynamic work and power, *Nature Communications*, 11(1): 1-12.
- [17] Bormashenko, E. 2019. The Landauer principle: Re-formulation of the second thermodynamics law or a step to great unification, *Entropy*, 21(10): 1-6. <https://www.mdpi.com/1099-4300/21/10/918>.
- [18] Newell, D.B., Tiesinga, E. 2019. The International System of Units (SI), NIST Special Publication, 330: 1-138. <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.330-2019.pdf>.
- [19] Lowrie, B. 2007. *Fundamentals of Geophysics*, Cambridge University Press, The Edinburgh Building, Cambridge CB2 8RU, UK.
- [20] Williams, D.R. 2017. *Earth Fact Sheet*, NASA/Goddard Space Flight Center.
- [21] Vopson, M.M. 2020. The information catastrophe, *AIP Adv.*, 10(8), 085014: 1-5. <https://sci-hub.se/10.1063/5.0019941>.
- [22] Vopson, M.M. 2019. The mass-energy-information equivalence principle, *AIP Adv.*, 9, 095206. <https://pubs.aip.org/aip/adv/article/9/9/095206/1076232/The-mass-energy-information-equivalence-principle>.
- [23] Landauer, R. 1996. Minimal energy requirements in communication, *Science*, 272(5270): 1914-1918. Doi: 10.1126/science.272.5270.1914.
- [24] Orlov A.S., and Orlov, S.A. 2019. Masses celestial bodies, *American Journal of Engineering Research and Reviews*, 2(15). DOI: 10.28933/ajoerr-2019-01-1208.
- [25] Kalf, F.E., et al., 2016. A kilobyte rewritable atomic memory, *Nature Nanotechnology*, 11(11): 926-929. <https://sci-hub.se/10.1038/nnano.2016.131>.
- [26] Seagate Introduces IronWolf Pro 22 TB HDD Offering Class-Leading Dependability and Performance, 2023. <https://www.seagate.com/em/en/news/news-archive/seagate-introduces-22tb-hdds-offering-cost-effective-scalable-capacity-pr/>.
- [27] Menin, B. 2019. On the Possible Ratio of Dark Energy, Ordinary Energy and Energy due to Information, *American Journal of Computational and Applied Mathematics*, 9(2): 21-25. Doi:10.5923/j.ajcam.20190902.01.
- [28] Menin, B. 2018. Bekenstein-Bound and Information-Based Approach, *Journal of Applied Mathematics and Physics*, Vol. 6(8): 1675-1685. http://file.scirp.org/pdf/JAMP_2018082114292484.pdf.