DEPARTMENT OF PHYSICS

Physics Pulse

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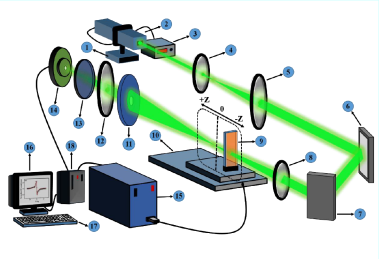
The Price of Knowing: When Thermodynamics Meets Information

By DR. AVIJIT MISRA

The quest for harnessing thermal energy efficiently for work extraction gave rise to the field of thermodynamics in the 19th century. The pinnacle of this quest was the second law of thermodynamics, which states that no process is possible whose sole result is the complete conversion of heat into work. In particular, it prohibits extracting work from a single heat bath, as that would imply full conversion of heat into work.

Patent Granted

We are delighted to share that **Nitesh Kumar Pathak, Priyadarshi Sahoo, and Prof. Umakanta Tripathy** have been granted a patent by the Patent Office, Government of India.



Patent Title: **A nonlinear optical tool to measure hemoglobin concentration in human ABO blood types**

Patent No.: 569424
Granted on: 31st July 2025
Congratulations to the team!

While several theories and concepts withered under the major breakthroughs in physics in the 20th century, thermodynamics has stood firm. Regarding its validity, Einstein once said: "The only physical theory of universal content, which I am convinced, that within the framework of applicability of its basic concepts will never be overthrown."

However, even this sacred theory faced an existential crisis which puzzled the scientific community for a century! In 1867, James Clerk Maxwell proposed a thought experiment, which he later elaborated on in his book *Theory of Heat*. In this thought experiment, a hypothetical being, later called a "demon" by Lord Kelvin, controls a small door in a chamber filled with an ideal gas at thermal equilibrium at a fixed temperature T (see first figure). The Maxwell's demon (MD) selectively allows only fast-moving molecules (with velocity greater than some threshold) to pass from the left side of the chamber to the right, while permitting only slow-moving molecules (with velocity below the threshold) to pass from the right to the left. As a result, the demon gradually accumulates faster, more energetic molecules on one side and slower, less energetic molecules on the other. In other words, he creates a temperature difference between the two sides of the chamber, even though the gas as a whole was initially in equilibrium at T. This artificially created temperature difference could, in principle, be exploited to extract work, but without the demon himself performing any mechanical work. Such an outcome contradicts the second law of thermodynamics, as it forbids the extraction of work from a single heat bath [1].

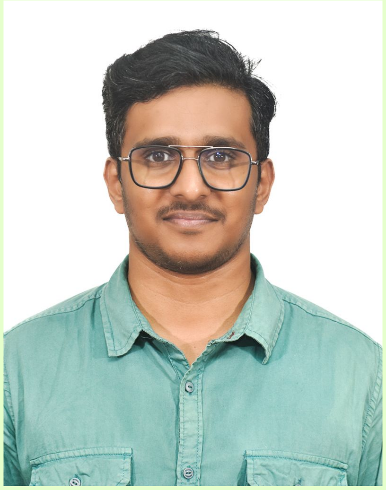
In 1929, Leo Szilard proposed a simplified version of the Maxwell's demon, called the Szilard engine. Instead of many gas molecules, he considered a box containing just one molecule of an ideal gas, in contact with a heat reservoir at temperature T. The working of the engine proceeds as (see second figure) follows:

INSPIRE Grant

Prof. Manu Kurian has been awarded the prestigious INSPIRE Research Grant (DST INSPIRE) for an individual research project.

Project title: **Exploring the intricacies of strongly interacting hot nuclear matter through heavy quark phenomenology in nucleus-nucleus collisions**.

Grant Duration: 5 years



Congratulations Prof. Kurian!

1. A partition is inserted into the middle of the box, dividing it into two equal halves. The single gas molecule will then be either on the left or on the right side, each with probability $\frac{1}{2}$.

2. The demon "measures" the position of the molecule and records whether it is on the left or the right.

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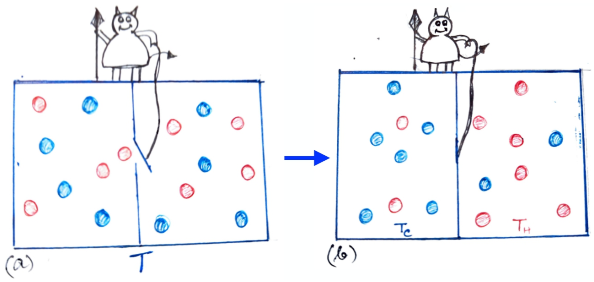
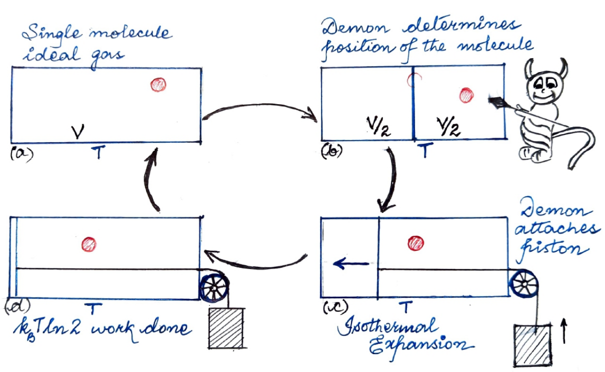
3. Depending on the measurement outcome, the demon connects a piston to the correct side. The molecule then pushes the piston isothermally, expanding from volume $\frac{V}{2}$ back to the full volume V. During this expansion, the engine extracts work $W = k_B T \ln 2$, where k_B is the Boltzmann constant.

4. After expansion, the piston is removed, and the box returns to its original state, ready for the next cycle.



The work comes from heat absorbed from the reservoir and thereby violates the second law.

This thought experiment puzzled the scientific community for almost a century! It was Rolf Landauer who in 1961 saved the second law of thermodynamics. Landauer argued that in a logically irreversible process, where a bit of information is erased, a minimum of $k_B T \ln 2$ energy is dumped as heat into the environment at absolute temperature T [2]. This would increase the entropy of the environment. This minimum amount of heat dissipated to erase one bit of information [1] is known as the *Landauer bound* (LB).



Now, let us revisit the Szilard engine. The demon acquires one bit of information by knowing the position of the molecule. To run the next cycle, the demon must erase its memory so that it can record the result of the next measurement. Note that an outcome-dependent action (attaching the piston) is essential for work extraction. According to the Landauer's erasure principle (LEP), the demon must expend at least $k_B T \ln 2$ energy to erase its memory. Interestingly, this is exactly equal to the amount of work extracted in the previous cycle [2]. Therefore, there is no net work gain from a single heat bath, and the second law remains safe. Thus, Landauer reconciled the Maxwell's demon with the second law.

It is important to mention that if we keep the demon's memory at a temperature T_C, where $T > T_C$, then one can, in principle, extract work by acquiring information and it is totally consistent with the second law of thermodynamics. This is the basic principle of all measurement-based heat engines, where information serves as a thermodynamic resource [3].

New BS-MS Program

The department launched a **5-Year BS-MS Dual Degree Program** new this semester. An orientation program was held on 30 July 2025, where the Head of the Department and faculty members welcomed the inaugural batch. During the session, they shared the department's vision, outlined expectations, and set the stage for what promises to be a transformative academic journey.

In addition, the department warmly welcomed the newly admitted students of the BTech (Engineering Physics) and MSc (Physics) programs.

In 1953, Leon Brillouin attempted to reconcile the MD with the second law by arguing that the demon must pay at least $k_B T \ln 2$ amount of energy to gain one bit of information. He further elaborated this concept as an entropic cost to acquire information, which is dubbed as the *negentropy principle*. It was Charles Bennet who showed in 1982 that the information gain and storage can be done reversibly in principle [4], and confirmed that only the erasure step must bear the entropic (energetic) cost. Thus, Landauer together with Bennet successfully exorcised the MD [5]. It established that "*Information is physical*", [6] not an absolutely mathematical concept that has nothing to do with physics.

Though now widely accepted for reconciling the MD with the second law, LEP faced various criticisms and objections in the early days. Two major objections were:

1. LEP is dependent on the second law of thermodynamics and thereby it can be considered to be either unnecessary or insufficient for "exorcism of Maxwell's Demon".

2. Thermodynamic quantities such as heat and work are fundamentally unrelated to mathematical concepts like logical irreversibility and information theory. Therefore, drawing direct parallels between them seems unfounded.

In [7] Bennet refuted all these criticisms.

There have been several fruitful explorations to establish LEP rigorously. An interesting generalization of the LEP has been done in 2011 by Vaccaro and Barnet [8]. They have shown that the information can be erased without energy cost, but with angular momentum cost. Specifically, angular momentum is exploited rather than energy for erasing information, and it is consistent with the second law of thermodynamics. In 2014, Reeb and Wolf [9] only assumed LEP in the quantum domain without resorting to the laws of thermodynamics. They only assumed that the memory to be erased and the environment are uncorrelated at the beginning, the environment is at a thermal equilibrium at a temperature T, and the memory and the environment evolve under unitary dynamics as prescribed by quantum mechanics. This is a significant step forward to study LEP in the quantum realm. It has spurred a huge interest among the scientific community. There have also been some experimental demonstrations of the LEP in both classical and quantum domains.

Physics in History

- **August, 1932:** Carl D. Anderson discovered the positron (antiparticle of the electron) using a cloud chamber and cosmic rays.
- **17 August, 1970:** The Soviet spacecraft Venera 7 was launched; it later became the first probe to transmit data from the surface of another planet (Venus).
- **18 August, 1868:** During a total solar eclipse, Pierre Janssen and independently J. Norman Lockyer observed a new spectral line in the Sun's chromosphere, leading to the discovery of helium.
- **23 August, 1966:** NASA's Lunar Orbiter 1 captured the first-ever photograph of Earth from lunar orbit ("Earthrise").
- **24 August, 2006:** The International Astronomical Union (IAU) adopted a new definition of "planet" and officially reclassified Pluto as a dwarf planet.

Importantly, the Landauer bound at room temperature is approximately 0.018 eV (2.9×10^{-21} J), whereas modern computers use a billion times more energy to erase a bit. The main reason for this is that the LB is achieved quasi-statically. In practice, we erase information in finite time, which increases heat production. At the miniaturized scale, this extra heat can damage the device or destroy the quantum resources when we encounter a logically irreversible step in a quantum computer. Therefore, approaching the LB in practical situations becomes important in low–energy-cost logical devices.

Moreover, memory erasure in finite time at small scales often drives the environment away from thermal equilibrium in both the stochastic and quantum thermodynamic domains. In these domains thermal fluctuations can no longer be ignored like in macroscopic systems. What will be the fate of LEP when we approach the absolute zero temperature or encounter information backflow from the environment (non-Markovian bath) to the memory register? Over the past two decades, there has been a spate of activities to investigate these fundamental but practically important questions. Interested readers may refer to a topical review [10] on recent progress in LEP in both stochastic and quantum domains.

References

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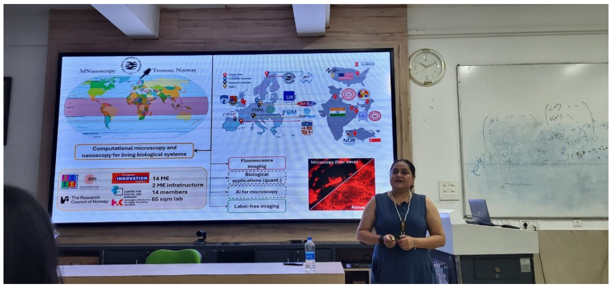
4. C.H. Bennett, Int. Jour. Theo. Phys. 21, 905 (1982)
5. R. Landauer, Phys. Tod. 44, 23 (1991)
6. A. Junior et al., PRX Quantum 6, 030201 (2025)
7. C.H. Bennett, Studies in Hist. and Phil. of Mod. Phys. 34, 501 (2003)
8. J.A. Vaccaro and S. M Barnett, Proc. Roy. Soc. A: Math., Phys. Engi. Sci. 467, 1770 (2011)
9. D. Reeb and M.M. Wolf, NJP 16, 103011 (2014)
10. P. Chattopadhyay, A. Misra et al., Rep. Prog. Phys. 88, 086001 (2025)

Research Talk



Dr. Krishna Agarwal, Professor at the Department of Physics and Technology, UiT- The Arctic University of Norway, visited the department as part of the Bioscopy Project – under the Indo-Norwegian cooperation programme.

Together with **Dr. Yingying Qin**, Dr. Agarwal delivered a captivating seminar on 30 July 2025, titled 'The Light of Life – Nanoscopy Techniques to Surpass Microscopy Limitations'.

Mr. Ankit Kumar Bera, a 3rd-year BS-MS student in the Department of Physical Sciences, IISER Berhampur, visited the department under the IIT(ISM) Summer Research Internship Scheme (SRIS) -2025 from May to July 2025.

Physics News

NISAR set to transform Earth Science

Carrying an advanced radar system that produces dynamic, three-dimensional views of Earth in unprecedented detail, the

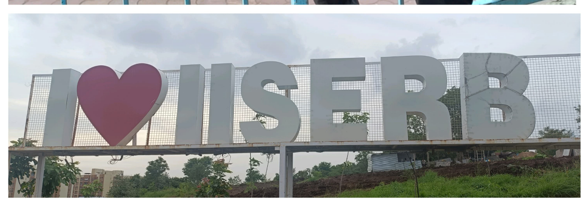
NISAR (NASA-ISRO Synthetic Aperture Radar) satellite was launched from the Satish Dhawan Space Centre in Sriharikota, Andhra Pradesh, India. The satellite lifted off aboard an ISRO GSLV-F16 rocket at **5:40 p.m. IST on 30 July 2025**. Jointly developed by ISRO and NASA, NISAR can detect land and ice-surface movements down to the centimeter. The mission's two radars will monitor nearly all of the planet's land- and ice-covered surfaces twice every 12 days, including regions in the Southern Hemisphere polar areas that are rarely covered by other Earth-observing radar satellites.

A Breakthrough in Quantum Computers

With the goal of reducing the number of qubits required, scientists at the University of Sydney have made a special logic gate using an error-correcting code called the GKP (Gottesman-Kitaev-Preskill) code. It lets them store and entangle two logical qubits. This helps detect and fix errors while using fewer physical parts, making quantum computing more efficient and compact. This is a major leap toward quantum computing, as it shows that it is possible to build smaller and more efficient quantum computers.

National Visits

Ashes Modak participated in the 9th edition of Student Talks on Trending Topics in Theory (ST4 2025), held at IISER Bhopal. The event provided a valuable platform for young researchers in theoretical physics to share their works and exchange ideas in areas such as SCFT (Superconformal Field Theory), AdS/CFT, Black Hole Thermodynamics, Scattering Amplitudes, and Matrix Models. As part of the poster session, Mr. Modak presented his work titled "A Note on Chaos in Hayward Black Holes with String Fluids," based on arXiv:2507.02716, co-authored with Dr. Aditya Singh and Prof. Binata Panda. The study explores how periodic thermal fluctuations can give rise to both temporal and spatial chaos in a regular black hole described by Hayward geometry and surrounded by a string fluid. Using the Melnikov method, it reveals signs of dynamical instability, including the presence of homoclinic and heteroclinic orbits. His poster sparked engaging discussions on black hole dynamics and the thermodynamic behavior of regular geometries.



Dr. Aditya Singh also contributed to ST4 2025. Student Talks on Trending Topics in Theory is a discussion meeting on theoretical physics organized by and aimed at advanced graduate students and postdoctoral fellows working in India and abroad. The meeting is similar in spirit to the Modave Summer School on Mathematical Physics, held annually in Belgium. It aims to provide an interactive environment for students and postdocs working in areas such as quantum field theory, general relativity, string theory, and related topics in mathematical and theoretical condensed matter physics.

Prasun Rajak had the opportunity to spend two months at the Physical Research Laboratory (PRL), Ahmedabad, as part of the Summer Research Fellowship Program from May 5 to July 4, 2025. Under the mentorship of Dr. Paramita Dutta, he worked on the topic "Altermagnetism: A Recent Discovery," exploring this novel third type of magnetic phase through theoretical insights and its implementation via magnetic symmetry order using minimal models.

Vrukshala Varshik Nath completed a summer internship at the Variable Energy Cyclotron Centre (VECC) in Kolkata. Working in the Theoretical Physics Division under the supervision of Dr. Jajati K. Nayak, his research focused on particle production in relativistic heavy-ion collisions, a key area in high-energy physics.

Tanuj Datta, a Ph.D student working under the guidance of Prof. Esha Kundu, presented an online Flash talk on "Investigating LMXRBs as plausible progenitors of FRB 20200120E" at the international conference, The Dynamic Radio Sky 2025, which took place at the University of Sydney, Sydney, Australia.

Research Publications

1. **Priyadarshi Sahoo, Nitesh Kumar Pathak**, Sunil Kumar Verma **Umakanta Tripathy**, Z-scan as a hemoglobin sensor: A simple and sensitive optical tool for measuring hemoglobin concentration in human blood, Journal of Applied Physics.
2. **V. Zimba, Meghana N., J. Nayak**, Enhanced room temperature formaldehyde gas sensing properties of hydrothermally synthesized WO3/ TiO2 hetero-nanostructures, Journal of Materials Research.
3. Tanmoy Pandit, Goutam Paul, **Avijit Misra**, and Pritam Chattopadhyay, Landauer principle and thermodynamics of computation, Reports on Progress in Physics.
4. Gershon Kurizki, Nilakantha Meher, **Avijit Misra**, Durga Bhaktavatsala Rao Dasari, Tomas Opatrny, Towards nonlinear quantum thermodynamics, The European Physical Journal Special Topics.
5. **Sheetal Sharma, Vinod Kumar Singh** and Manoj Kumar Gupta, A flexible MXene–carbon nanotube-based triboelectric nanogenerator for self-powered pH sensors, RSC Nanoscale.

Physics Job Openings

1. **Field Applications Engineer at Thermo Fisher Scientific, Bengaluru**:
   Skills Required: Hands-on experience with SDB, semiconductor process development, failure analysis; excellent communication and customer support skills.
   Eligibility: Physics graduates with strong analytical abilities and technical curiosity are well-suited for this role.

2. **Quantum Technology Tutor at QpiAI, Bengaluru**:
   Skills Required: Basics of quantum computing (e.g., Amazon Braket), Python programming, knowledge of quantum mechanics, and good communication skills.
   Eligibility: Suitable for Physics graduates who enjoy learning and explaining exciting science topics.
   Role Summary: Assisting students and professionals in understanding and engaging with the world of quantum technology.

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