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GUEST EDITORIAL

Engine

The word ‘engine’ implies locomotion. Indeed trains powered by engines occupy a special place in our lives. They evoke romanticism of poetry, novels and Bollywood films, including some memorable songs that have been tuned with the whistling sound of engines. *Time* magazine once carried a cover story on Indian trains laden with delightful anecdotes. It narrates how job discussions, interview preparations, marriage negotiations, political wheeling and dealings, business transactions, etc. are all carried out inside railway compartments. The noted mathematician, historian and philologist D. D. Kosambi receiving mail from the Postal Department, on his regular sojourn in the ‘Deccan Queen’ between Poona and Bombay, is now a legend.

Engines are associated with the onset of the industrial revolution. The underlying scientific idea of an engine rests on how it converts heat into mechanical work, thus linking the idea with thermodynamics, the mother of all sciences that embraces macroscopic phenomena of physics, chemistry and biology. The first two laws of thermodynamics teach us that not all of the heat supplied to a system can be converted to work because of what is known as ‘entropy-loss’. Indeed the ratio of the work to the heat input is known as the efficiency of the engine. The endeavour of technology is to push the efficiency closer and closer to 100% – a theoretically unreachable limit.

The concept of entropy is quite a subtle one which we struggle to communicate to our undergraduate students in the first course on thermodynamics. All that is conveyed is the abstruse notion of entropy being a measure of ‘disorder’. In fact, until we begin teaching statistical and quantum mechanics, entropy remains an enigma. Boltzmann is undisputedly one of the founding fathers of statistical mechanics. However, it is the hostile reaction to his formula of entropy – in terms of the logarithm of the total number of accessible micro states in the phase space – that drove Boltzmann to suicide. Today statistical mechanics is viewed as the microscopic basis of thermodynamics, though vexing questions such as of ergodicity continue to defy exact analysis. Quantum mechanics, the foundation of which still triggers animated debates, puts the issue of entropy on a different footing – it reinterprets the Boltzmann formula in terms of the degeneracy or the number of distinct states associated with an energy level.

Concurrently with the development of thermodynamics occurred the invention of a plethora of engines – Carnot, Otto, Rankin, Stirling, Ericsson, etc. about 200 years ago. These engine cycles employ various thermodynamic processes like isobaric (constant pressure P), isothermal (constant temperature T), isochoric (constant volume V), and isentropic (constant entropy S). All these aforesaid engines have a varied degree of efficiency. The Carnot cycle (1824) comprising two isothermal processes at temperatures T_c (‘cold’) and T_h (‘hot’), sandwiched between two isentropic processes, sets a maximum bar on the efficiency given by $(1 - T_c/T_h)$. Indeed the mathematical treatment of the Carnot cycle by Clausius (1857) led to the concept of entropy.

While technology continues to strive at developing more and more efficient engines, recent scientific attention has focused on their biological counterparts. Unlike the familiar cycles such as Carnot, Stirling, Rankin, etc. that deal with macroscopic thermodynamic variables, the biological engines are micro objects, albeit in a macroscopic environment. These are protein machines which are essential agents of motion in living matter. Like the usual engines, the biological engines also consume energy and convert it into mechanical work, but this energy is in chemical form, released by the hydrolysis of adenosine triphosphate (ATP) or guanosine triphosphate (GTP). There are various types, the prominent among which perform cytoskeletal motion, e.g. myocin in the muscles and kinesin that transports cargo inside cells away from the nucleus along microtubules. Another important candidate utilizes polymerization such as in DNA, in actin (using ATP) and in microtubule (using GTP). Biological engines are superior in efficiency compared to man-made engines.

Interestingly, biological engines are of nano size – of the order of 10^{-9} m. On this length scale, new and challenging physics emerges. For instance, the surface-to-volume ratio is non-negligible and hence all ‘macroscopic’ theories such as elasticity, thermodynamics, electrodynamics, etc. require a relook when it comes to describing intra-engine physical phenomena. Besides, biological engines need a liquid medium with specific salt composition, temperature and pH, and therefore, they are necessarily immersed in a heat bath. The bath is characterized by omnipresent noise and thermal fluctuations.

Like the pollen grains in a jar of water that Brown had observed to undergo what is now called Brownian motion – almost two centuries ago – the nano biological engines also have similar size-ratio compared to the molecules of the bath. Hence, Brownian motion is a quintessential ingredient in the functioning of such devices. It is not surprising then that Brownian engines are one of the most investigated contemporary topics of nano science.

Brownian motion is a paradigm of irreversible phenomena in the realm of non-equilibrium, dissipative statistical mechanics. Systems such as the pollen grains in Brown's experiment encounter friction that is determined by the viscosity of the surrounding liquid medium via Stoke's relation. As a result, the grains undergo diffusive motion governed by equations that do not obey time-reversal invariance. That is to say the equations of motion do not remain the same – an attribute that is considered sacrosanct for microscopic dynamics – when the time variable is reversed in sign. The underlying theoretical framework is based on what are called stochastic processes, the foundation of which was laid by Einstein (1905). The study of biological engines is thus inseparable from the analysis of Brownian motion which yields a gamut of behaviour ranging from ballistic to diffusive (Einstein) regime.

Biological Brownian engines have been investigated by novel experimental techniques of optical and magnetic tweezers, fluorescence resonance energy transfer, fluorescence correlation spectroscopy, total internal reflection fluorescence, neutron spin echo spectroscopy, scattering techniques involving interference, etc. The probing of nano engines has generally come to be classified as single molecule spectroscopy. Inspired by the exciting science that can be done with biological engines and the need to perform controlled experiments in the laboratory, recent years have seen fascinating efforts to realize a Stirling engine in the form of a colloidal particle (Blickle and Bechinger, *Nat. Phys.*, 2012, **8**, 143). Instead of being nano-sized, these colloidal particles are of micrometre in size. Using the radiation pressure exerted by laser fields on the particle, one can implement optical tweezers that mimic a harmonic trap for the particle. The curvature of the harmonic potential that can be manipulated in the laboratory is employed to generate isochoric processes of a Stirling cycle.

In India too we have witnessed significant experimental advances in gaining improved efficiency of artificial engines of micro size. Replacing the environment by swarms of bacteria, Krishnamurthy *et al.* (*Nat. Phys.*, 2016, **12**, 1134) have shown how the baths are driven out of equilibrium. The surrounding noise thus acquires a non-Gaussian character, which causes a substantial rise in the efficiency of the underlying Stirling engine. These and the earlier mentioned novel laboratory attempts have occasioned and given directions to new developments in the subject of thermodynamics itself. Normally, thermodynamics does not incorporate dissipative parameters such as friction, diffusion coefficient, etc. That is because Gibbs' statistical mechanics, that subsumes thermodynamics, assumes that the system of interest is only weakly coupled with the environment. However, when the system of interest is a single particle of nano or micro size, the coupling and resultant environmental effects are inevitably strong and hence dissipative parameters are an essential component of thermodynamic relations, giving rise to a new subject called stochastic thermodynamics (Sekimoto, *Lect. Notes Phys.*, Springer-Verlag, 2010, 799; Seiffert, *Rep. Prog. Phys.*, 2012, **75**, 126001). Stochastic thermodynamics reinterprets the basic thermodynamic equality $\mathrm{d}Q = \mathrm{d}U + \mathrm{d}W$, such that the differential heat input $\mathrm{d}Q$, differential energy $\mathrm{d}U$ and differential work $\mathrm{d}W$ are all viewed as noisy, fluctuating quantities.

Stochastic thermodynamics is particularly important in the context of a quantum particle in a dissipative bath that is also quantum mechanical, giving rise to a subject called quantum thermodynamics (Gemmer *et al.*, *Lect. Notes Phys.*, 2004, 784). An example is that of an electron in a harmonic trap, but further subjected to cyclotron motion due to an applied magnetic field. The quantum bath is that of a bunch of phonons or quantum harmonic oscillators. The magnetic field mimics the pressure P of an Ericsson engine, for instance (Dattagupta and Chaturvedi, 2017, arXiv: 1712.05543). The combination of quantum mechanics, nano science and stochastic thermodynamics is expected to lead to challenging times in the theoretical study of Brownian engines. It would also have deep implications for quantum information processes.

Summing up, we have come a full cycle (pun intended) – spanning almost two centuries of the history of locomotive engines, thermodynamics and independently, Brownian motion – to arrive at a juxtaposition of exciting science and its influence on sociologically beneficial engines with much improved efficiency. If Carnot and others ushered in the first industrial revolution in the beginning of the 19th century, Faraday led the second one by combining electromagnetic power with mechanical motor action. More than a century later, we saw the advent of the third industrial revolution with the discovery of transistors by Bardeen *et al.* that transformed electronics. A decade later, the unravelling of the DNA structure by Crick and Watson altered our understanding of life. In this millennium, we are witnessing the onset of the fourth industrial revolution in which DNA-based molecular engines, in combination with microelectronics, are expected to change the face of nanotechnology and its deep impact on mankind.

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