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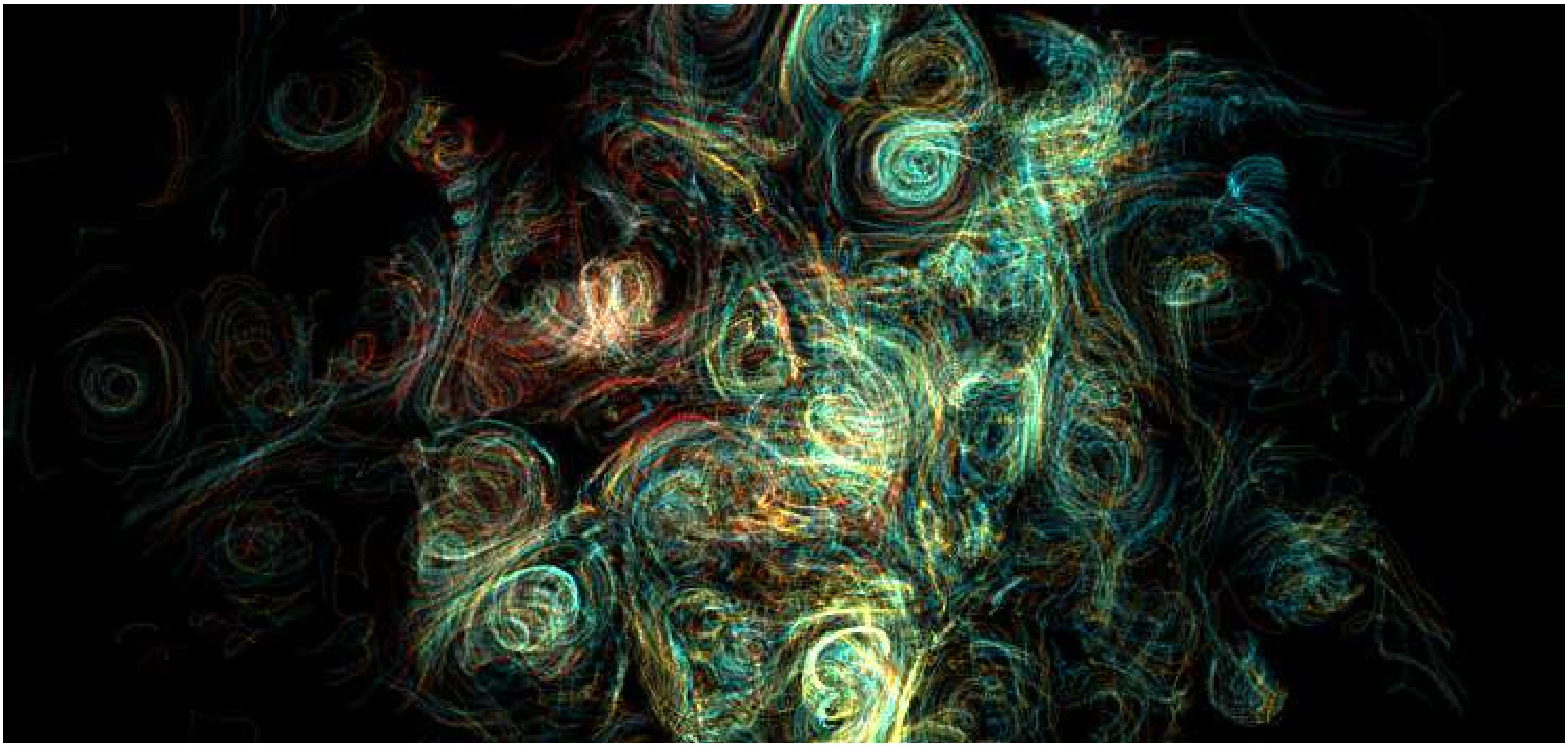

CAN LIVING FLUIDS BE TURBULENT?

SIDDHARTHA MUKHERJEE AND SAMRIDDHI SANKAR RAY

A little over a quarter of a century ago a remarkable thing happened. Our fascination for the intricate, orderly motion of fish schools and bird flocks found expression in the precise language of statistical physics [Vicsek *et al*., Phys. Rev. Lett. **75**, 1226 (1995); Toner & Tu, Phys. Rev. Lett. **75**, 4326 (1995)]. Just as the tools of Renormalization Group revolutionized our ideas of scales and symmetries in *inanimate* matter, this *new physics* set up the formal machinery to understand the spectacularly elegant, emergent phenomena which seems equally *universal* in living, out-of-equilibrium *active* matter systems. The seminal pioneering papers on active matter – simply defined as systems composed of internally driven constituents (at cellular or macroscopic scales such as swimming fish) which self-organize leading to large-scale correlated motion – laid a remarkably robust foundation of a microscopic and hydrodynamic theory and helped construct the edifice of this new, exotic branch of non-equilibrium condensed matter physics which makes a direct contact with the world of the living [Ramaswamy, Ann. Rev. Cond. Matt. Phys. 1, 323 (2010); Marchetti et al., Rev. Mod. Phys. 85, 1143 (2013)].

Against this backdrop, a new set of experiments and visualization of (dense) bacterial suspensions provided much food for thought [Alert, Casademunt, and Joanny, Ann. Rev. Cond. Matt. Phys. **13**, 143 (2022)]. Such suspensions are a good example of active matter: Its constituents, the individual bacterium, are active and *move*. Remarkably, *bacterial flows* seemed to show large-scale coordinated motion and elements of spatio-temporal chaos. Soon enough, several such *living* and *active fluids* were discovered showing intricate and chaotic motion at scales larger than their constituent elements: Bacterium, microtubules, sperms, or even self-propelled Janus particles. While these flows are decidedly sluggish, or more precisely at very low Reynolds numbers, they do bear a striking resemblance to what high Reynolds number, inertial, classical turbulent flows look like. Indeed, one cannot be faulted if one mistook a video of, for example, a two dimensional bacterial suspension [Wensink *et al*., PNAS, 109, 14308 (2012)] for a turbulent soap film [Perlekar *et al*., Phys. Rev. Lett. 106, 054501 (2011)]. All of this lead to the now commonplace nomenclature of this phenomenon – the emergent spatio-temporally chaotic flow in active matter suspensions – as *active turbulence*[1].

To help the reader appreciate the excitement and the perhaps immediate association of bacterial flow with turbulence, in Fig. 1 (a) we show a snapshot from our own experiments (carried out at the National Centre for Biological Sciences (NCBS) in Bangalore in partnership with Shashi Thutupalli and Suresh N.) of a suspension of *E. Coli* bacteria (strain W3110)[2]. A cursory glance of such a snapshot impresses on us – especially when we see the swirling vortices – the striking familiarity with a high Reynolds number inertial turbulent flow (Fig. 1(c)) obtained from (in-house) simulations of the all too familiar two-dimensional, incompressible Navier-Stokes equation. This comparison becomes all the more compelling when we compare Fig. 1(c) with Fig. 1(b); the latter being a snapshot from simulations of hydrodynamic equations [Wensink *et al*., PNAS, 109, 14308 (2012)] which model the kind of bacterial flow shown in Fig. 1(a)[3].
But are these flows truly turbulent or are they, for example, more similar to chaotic flows of polymer solutions at low Reynolds number? High Reynolds turbulence of inanimate liquids and gasses sits on a pedestal as a grand old, and yet unsolved, problem of classical physics. Should these new active fluids find a place in that pantheon? This is not just a question of semantics because it informs new physics – especially from the point of view of universality – and in reassessing the tools that have been applied to both.

This question is arguably an open and subjective one. The answer lies in confronting such suspensions with tell-tale signatures of inertial (high Reynolds number) turbulence which go beyond *just* a visual impression of spatio-temporal chaos. Fully developed turbulence is also intermittent, (approximately) scale-invariant, and associated with a universal scaling exponent of the energy spectrum (i.e., the kinetic energy content in different Fourier modes) at scales intermediate between the energy injection and energy dissipation wavenumbers — all of this makes it unique amongst all classes of driven-dissipative systems[4]. The last of these features, namely scale separation, is clearly absent in the turbulence of a bacterial suspension: Energy injection (through the active constituents) occur at scales comparable to those where energy is damped.

For a theorist to tackle such questions we must begin with equations of motion which describe the emergent *continuum* velocity fields of these active fluids. However, even at the coarse-grained hydrodynamic description of such systems, the right equation for different systems are different. Given our bias for bacterial suspension in this article, we focus on the theoretical work which has emerged from a generalized Navier-Stokes-like field equation for the coarse-grained velocity field **u** of a two-dimensional bacterial suspension which factor in the active energy injection term and those which lead to instabilities. For simplicity, we will use the symbol α< 0 in this article as a short-hand to denote how fast or active the constituent bacterium is in these fluids. [5]

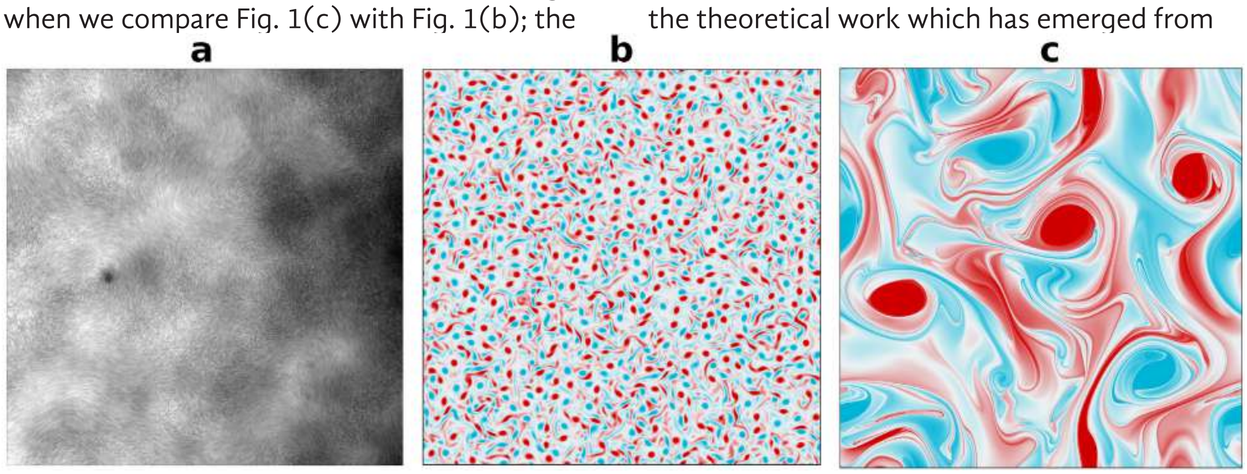

Figure 1: Snapshots of the bacterial flow from (a) experiments at NCBS with dense suspensions of *E. Coli* and (b) simulations of the generalised hydrodynamics model which describe such flows [Mukherjee et al., Phys. Rev. Lett. **127**, 118001 (2021)]. The panel (c), for comparison, is a snapshot from our simulations of extremely high Reynolds number two-dimensional inertial turbulence forced at large scales.

Homogeneous and isotropic, high Reynolds number inertial turbulent flows, since the seminal 1941 work of Kolmorogov, are known to obey an (approximate) scale invariance with a universal scaling exponent of the power-law behaviour in the distribution of kinetic energy across Fourier modes which are far away from the smallest and largest scales in the problem [U. Frisch, *Turbulence* (Cambridge University Press, Cambridge, UK, 2004)]. As far as we can tell, should such a scale separation (between the energy injection and dissipation scales) exist, this spectral exponent, for different flows and different Reynolds numbers, are universal. With this spectre of Kolmogorov looming large, the question of a similar universality in active turbulence – at least the ones described by a generalized Navier-Stokes-like hydrodynamic equation – was investigated recently [Bratanov, Jenko and Frey, PNAS 112, 15048 (2015)]. In a wonderful analysis, which combined phenomenological ideas and rigorous calculations, the authors showed that the energy spectrum –

$$E(k) = \frac{1}{2}\sum_{k'=k-1/2}^{k+1/2} \langle \mathbf{u}(\mathbf{k}') \cdot \mathbf{u}(\mathbf{k}') \rangle \sim k^{\delta}$$

are characterised by scaling exponents which depend on the level of activity α and hence lack the universality associated with classical turbulence. While this is certainly true for mild activity [Bratanov, Jenko and Frey, PNAS 112, 15048 (2015)], beyond a critical (experimentally realisable) level of activity α_c, a recent study [Mukherjee *et al*., ArXiv: 2207.12227] suggests that such suspensions reach an asymptotic state with a unique scaling exponent. In particular, the scaling exponent is shown to obey the following form (the different coefficients in the formula for relate to the properties of the system and are unimportant in the present context):

$$\delta = \begin{cases} \frac{\tau_{\rm eff}(2\alpha + 8\beta E_{\rm tot})}{\lambda} - 1 \gtrsim 0 & \alpha \gtrsim \alpha_c \\ -3/2 & \alpha \lesssim \alpha_c \end{cases}$$

Such universal, scale-invariant asymptotic states, form the foundations of high Reynolds number, inertial turbulence theories. However, we also know that fully developed turbulence has a second fingerprint, namely intermittency which results in velocity gradients and fluid accelerations having probability distributions with *fat*, non-Gaussian tails. If indeed bacterial suspensions do have a more turbulence-like asymptotic state, can intermittency be far behind? Recent measurements [Mukherjee *et al*., ArXiv: 2207.12227] of the distribution of velocity gradients in numerical simulations of such flows suggest clear departures from Gaussianity when suspensions are driven to values of activity beyond the critical value α_c. Such suspensions, when highly active, thus show remarkable similarities to inanimate turbulent flows while also being maximally chaotic at the transition α_c. This last element in this story is particularly intriguing. Most

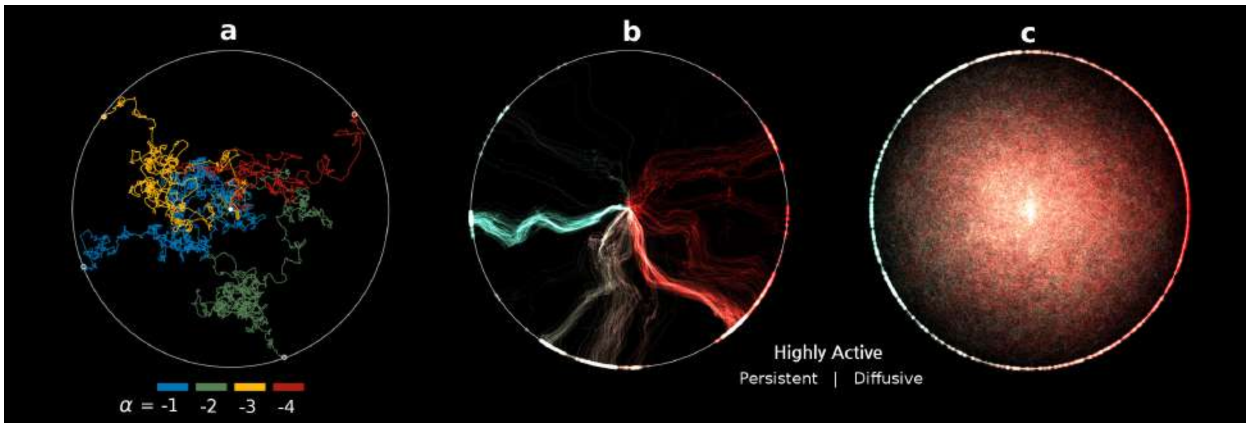

Figure 2: Representative trajectories from simulations of (a) active turbulence with varying levels of activity and the (b) fastest and (c) slowest 1% of trajectories. Clearly, the faster ones are persistent and anisotropic while the slower ones are diffusive and isotropic. All trajectories, for easy visualisation, have been translated to the same origin and the variation of color is proportional to the angle at which they reach the boundary. [Singh, Mukherjee and Ray, Phys. Rev. Fluids 7, 033101 (2022)]

theories as well as evidence from simulations suggest that the degree of chaos – as measured by the Lyapunov exponent – grows with Reynolds number. Active turbulence seems to rebel at this notion of unbounded growth. Thus active turbulence seems to be rich and riddled with surprising nuances, which at times bridge the analogy with inertial turbulence (emergent universality, intermittency), and at times break it (maximal chaos).

All of this is fascinating for those of us working in high Reynolds flows with our feet firmly grounded in statistical physics. But how conversant are the poor bacteria with such matters and can they exploit this to their advantage? In particular, can they reap benefits for essential functions like foraging and evasion by using the emergent states at high enough activity? One possibility is to see if the emergent hydrodynamics of such suspension allow the bacteria to overcome the limitations of diffusive behaviour in their struggle for survival. Indeed, anomalous diffusion and Lévy walks [Zaburdaev, Denisov, and Klafter, Rev. Mod. Phys. **87**, 483 (2015)] are commonplace in a wide variety of biological systems, often as an optimal strategy for foraging and survival. Thus it is worth pondering that even if the individual can fail to go beyond random walks, could deviations from simple diffusion arise as an emergent phenomenon in their collective, fluid-like state.

The first major insight that such behaviour is possible came from a set of experiments [Ariel et al., Nature Comm. 6, 1 (2015)] a few years ago. By fluorescently labelling *B. subtilis* cells, Ariel and collaborators recorded swarming trajectories showing clear evidence of Lévy walks[6] and an accompanying super-diffusive behaviour as measured through the mean-squared displacement

$$\Delta x^2 = \langle ||\mathbf{x}(t) - \mathbf{x}(0)||^2 \rangle \sim t^\xi$$

where $\|\cdot\|$ and $\langle\cdot\rangle$ denote Euclidean norm and ensemble averaging, respectively) with $\xi \approx 1.6$ beyond the ballistic regime. It is only recently [Mukherjee et al., Phys. Rev. Lett. 127, 118001 (2021)] that the theoretical underpinnings of this behaviour and the mechanisms of anomalous diffusion and Lévy walks were discovered through extensive numerical simulations and Lagrangian analysis of the generalised hydrodynamic model for such systems. Associated with anomalous diffusion, the authors also uncovered a novel, fundamental feature in the bacterial flow where, along with the usual spots of vorticity, oscillatory *streaks* emerge. While the former is reminiscent of inertial turbulence, the latter is unique to active turbulence. Thus as bacteria begin to push harder, their colonies fundamentally alter their collective flow[7]. Meandering diffusion then gets abandoned in favour of highly specialized movements marked by long, straight excursions and sharp turns resulting in Lévy walk dynamics. This enhanced behaviour allows bacteria to travel farther and is enabled by a novel pattern emerging in the collective flow. Quite amazingly, while some aspects of active turbulence still emulate classical turbulence, Nature circumvents the latter's limitation of classical diffusion. This is borne out most starkly when questions of first-passage are addressed for such suspensions [Singh, Mukherjee and Ray, Phys. Rev. Fluids 7, 033101 (2022)].

The story of active turbulence and its many avatars, especially in the light of several interesting observations and results in the last two years [e.g., James et al. Nat. Comm. 12, 1-11 (2021); Alert, Joanny, and Casademunt, Nat. Phys. 16, 682 (2020) and [Bourgoin *et al.*, Phys. Rev. X 10, 021065 (2020)], is a delightful one. We have only touched upon some aspects of this story which are in direct contrast to what happens in inanimate, inertial turbulence. The coming years will hopefully lead to many more answers at the interface of biology and physics, eventually shedding light on how well a swarm of bacteria knows its statistical physics.

So are living fluids turbulent? The answer is perhaps a cautious yes and may well lie in the eyes of the beholder.

Footnotes

1 In what follows, we discuss these ideas in the light of recent results and, for clarity, use bacterial suspensions as a point of reference.

2 This is imaged at 25-100 frames-per-second in bright field at a resolution of 10x and 40x (1.333 mm and 0.330 mm viewing window edge).

3 We deliberately show larger vortices in the turbulent ow (Fig. 1(c)) when compared to the bacterial ow (Figs. 1(a) and (b)) by using a large-scale forcing which is distinctly different from the small scale energy injection in a living fluid.

4 The extent of this scale separation between the injection and dissipation wavenumbers increases with increasing Reynolds numbers.

5 We refer the reader to the work of Wensink et al., PNAS, 109, 14308 (2012) for a description, derivation and validity of the phenomenological Navier-Stokes like equations that describe such flows.

6 A continuous-time random walk with constant speeds punctuated by sharp turns; the turning times show a power-law distribution.

7 See also Synopsis: Bacteria That Shove Harder, Move Further, Physics 14, s116 (2021)

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EMERGENCE OF WESTERN SCIENCE IN INDIA

SREERUP RAYCHAUDHURI

What is called 'science' across the world today should, strictly speaking, be called 'Western empirical science'. This is actually a fairly recent phase in the intellectual development of the world, though its roots run deep. Western empirical science originated in Europe about five centuries ago, and marked a conscious separation between pure empiricism and the large admixture of mysticism which had characterised the thinking patterns of preceding ages. Quite naturally, empirical science as an intellectual movement had no aficionados among Indians till the nineteenth century. This is not to say that scientific *results* were unknown in India before that - quite the contrary, in fact. However, science and spirituality, empiricism and pantheism had always been mixed up in the earlier ages. Thus, the truth is that modern science was imported into the subcontinent by European invaders and initially espoused by only a small section of the Indian middle classes. Then it increasingly grew into a country-wide movement. These developments form the subject of the present article.

Presidency College

Tentative Beginnings

James Rennell

As a mark of gratitude for helping him to acquire the throne of Bengal (1757), Nawab Mir Jafar awarded the English East Indian Company a tract of land comprising 24 *parganah*s (subdivisions), to enjoy its revenues unimpeded. In pursuit of this, Bengal Governor Robert Vansittart brought in a young seaman, James Rennell, to survey and draw detailed maps of the area and determine the exact amount of tax (1764). It was Rennell who drew the first detailed scale maps of not just the British demesne, but also of much of Bengal and eventually of much of India. Thus, Rennell may be described as the first practitioner of Western science in India. He was followed, in 1800, by '*The Great Trigonometric Survey*', which brought scientific surveying to all of the Indian subcontinent. Its founder was Colonel William Lambton, a Yorkshireman who, starting from the mount of Mylapore in Madras, carried out his work diligently, but had only reached Central India when he died of malaria in 1823. His unfinished work was completed by his sickly and cantankerous but supremely able deputy, Colonel (later Sir) George Everest. It was Everest who became the first Surveyor-General of India. The Survey of India, which he founded, may fairly be considered the first scientific institution in the subcontinent.

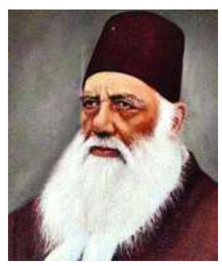
Radhanath Sickdher

Everest's successor at the Survey was Colonel (later Sir) Andrew Scott Waugh, who had a passion for measuring the Himalayan peaks. Waugh found that there was a peak – Peak XV – in the Himalayas on the Nepal-Tibet border, which had been estimated by his surveyor John Nicholson to be 30,000 ft high. However, these measurements had been made from more than a hundred miles away, and therefore, required corrections – a job given by Waugh to his best mathematician — a Bengali polymath named Radhanath Sickdher. This Radhanath, who was the first native-born Indian to practice Western science in India, found the Peak XV to be 29,002 ft high, making it the highest mountain in the world — Mt. Everest (1852). We may note that Radhanath was not the discoverer of Mt. Everest, nor the first to identify it as the highest in the world, but he was definitely the leader of the team which found its exact height. More importantly, he was the first native-born Indian to demolish the then-prevalent colonial myth that the Indian mind tends to mysticism and not to practical matters. He has been the role model for all Indian scientists ever since.

Western Education

The phenomenon of Radhanath Sickdher would not have been possible unless he had been trained in science by a professional. This was John Tytler, a surgeon-turned-mathematician who had been roped in to teach at the so-called *Hindu Mahapathshala* or Hindoo College, as the British called it. This institution was founded , with generous grants from rich Hindu *zamindar*s in 1817, renamed the Presidency College in 1959 and it became the Presidency University in 2010. Once Governor-General Lord Auckland made English compulsory for all official transactions (1837), colleges proliferated all over India during the nineteenth and early twentieth centuries. The Jesuit fathers founded a St. Xavier's College at Calcutta (1860) and another one at Bombay (1869), and a Loyola College at Madras (1925). Scottish presbyterian missionaries founded the Scottish Church College at Calcutta (1830) while Anglican missionaries started the Wilson College at Bombay (1834), the Madras Christian College (1837) and St. Stephen's College in Delhi (1887). Rich locals and landlords helped to start the Presidency College at Madras (1847) and the Elphinstone College at Bombay (1840). The first science college — the Robertson College, now Government Science College– was founded at Sagar in 1836 and later transferred to Jabalpur in 1873.

Initially Muslims, unhappy over the loss of dominion of their co-religionists to the foreigners, stood aloof from the alien learning.



Syed Ahmed Khan

The Anglo-Mohammedan College, founded in Calcutta (1780) by Warren Hastings (which later became the Calcutta Madrasah, and from 2008, the Aliah University), stubbornly remained a centre for teaching Persian, Arabic and Islamic law. Only in 1878, Sir Syed Ahmed Khan, in response to the promptings of poet Mirza Ghalib, founded a Mohammedan Anglo-Oriental College at Aligarh, to bring the new learning to Muslim boys. This metamorphosed into the Aligarh Muslim University in 1920. Syed Imdad Ali was instrumental in founding the Langat Singh College at Muzzafarnagar (1899). From this point, the Muslim community never looked back.

Education of women came somewhat slower. The pioneering Wesleyan College for Women had been founded in America in 1836 and the Bedford College at London in 1849, but the first Indian school for women in Calcutta had to wait till 1879 for the initiative of John E. Drinkwater Bethune — it later grew into the Bethune College. By 1895, the Sarah Tucker College was operative in Tirunelveli. The SNDT Women's University – the first women's university –was started in Bombay in 1916 by *Maharshi* Dr. Karve.

After the War of 1857, three Universities were founded at Calcutta, Bombay and Madras (1858). These awarded graduate degrees to students in the various affiliated colleges springing up across the country. The Calcutta University, in particular, served affiliated colleges spread from Lahore to Chittagong, and from Shimla to Batticaloa. For postgraduate studies, however, a student still needed to go abroad — to Britain, and in some cases, to the United States.

It was in these new educational institutions that the scientific future of India was forged. Students learned the English language and were given an introduction to the sciences and to European philosophy, especially the thinking patterns of the Enlightenment. The most important aspects of this were the importance of empiricism and transparency in method. Gone were the days of miraculous powers and intuitive knowledge transcending the five senses. The more receptive of Indian students soaked up this culture like sponges and were soon willing to try their own hand at making new discoveries alongside their European peers.

The Pioneers

While it is true that Radhanath Sickdher had developed his own methods to correct raw surveyor's data for effects like the curvature of the Earth and atmospheric refraction, the first original work – of mathematics – was published (1859) by a long-forgotten mathematician called Ramchundra Lall. Titled 'A *Treatise on Problems of Maxima and Minima, solved by Algebra'*, it was recognised as a work of great originality by the famous English mathematician Augustus de Morgan, but is little remembered today. After a gap of many years, a young graduate from Calcutta University named Asutosh Mookerjee started publishing papers in mathematical journals, including '*A note on elliptic functions*' which earned the praise of no less a personage than Arthur Cayley. These may be considered the first Indian scientific publications in the modern sense. Their author, later Sir Asutosh, soon quit mathematics to become a renowned lawyer and a judge, and then returned to academics as Vice Chancellor of Calcutta University. In this role, he created the first postgraduate departments of science — physics, chemistry, mathematics, botany and zoology — in India.

Ramchundra Lall

Contemporary with Sir Asutosh was Sir Prafulla Chandra Ray, better known as *Acharya* Prafulla Chandra. Ray was an inorganic chemist *par excellence,* who completed a Ph.D. from Edinburgh University (1887) and then returned to Presidency College, Calcutta, where he managed (1895) to synthesise mercurous nitrate ($HgNO_2$), previously thought to be an impossible compound. He was also an entrepreneur who founded the Bengal Chemical & Pharmaceutical Works (which still exists), and an antiquarian who wrote '*A History of Hindu Chemistry*' as well as a magnetic teacher who groomed the formative years of a generation of chemistry pioneers. These included Nil Ratan Dhar — physical chemist, Sir Jnanendra Chandra Ghosh — electrochemist, Jnanendra Chandra Mukherjee — colloid and soil chemist and Bires Chandra Guha — biochemist. It was these successors who really built up Indian chemistry and took it to the international stage.

Prafulla Chandra Ray

Larger than life on the same international stage was Sir Jagadis Chunder Bose, or *Acharya* Jagadis Chandra, who studied under Lord Rayleigh at Cambridge and returned to Presidency College to start work on electromagnetic waves. He was the first to construct a practical radio receiver, which he called the '*mercury-ion coherer*'. It was with this receiver — which Bose had declined to patent — that Guglielmo Marconi built the first radio and transmitted a signal across the Atlantic Ocean. Bose went further to study microwaves, in the course of which he created devices such as the horn antenna, dielectric lenses, waveguides, etc. and pioneered the use of galena (ZnS) as a semiconductor. Sadly, the Nobel Prize for radio went to Marconi — and it was shared with Ferdinand Braun for the discovery of galena as a semiconductor. Only in 2012 was Bose finally recognised by the IEEE as the '*Father of Radio Science*', and a plaque to this effect was set up at the Presidency College next to the laboratory where he had worked.

Jagadish Chandra Bose

However, during his lifetime Bose was best known for his studies of plants and how they respond to external stimuli. He built extremely sensitive instruments which amplified and recorded the most minute movements of plants by some 3 to 4 orders of magnitude. With these, he was able to show that plants have a slow pulse and circulation of sap, that they shudder and convulse when cut or torn, that they undergo contractions like death throes when poisoned, and that they can communicate by electrochemical messengers, i.e., they resemble animals much more closely than was thought earlier. Bose's work was received with awe at first, then scepticism and finally outright rejection in the West. It's only in the past few decades that some of his most important results have reappeared as the novel subject of plant neurobiology — set up by Western scientists, of course. However, this still has its detractors, including some very eminent ones.

The example of Bose set off an efflorescence in physics in the early part of the twentieth century. These are all names to conjure with — Meghnad Saha, discoverer of the Saha ionisation formula, Satyendra Nath Bose, inventor of quantum statistics, Prasanta Chandra Mahalanobis, inventor of the measure in statistics, Debendra Mohan Bose, pioneer of cosmic ray studies, Sisir Kumar Mitra, discoverer of the E-layer in the ionosphere. Then came Chandrasekhara Venkata Raman and Kariamanikkam Srinivasa Krishnan, co-discoverers of the Raman effect, followed by Bidhu Bhushan Ray, who proved that the Raman effect extends to X-rays. The climax came when Raman won the 1930 Nobel Prize — almost a century ago. Till date, no Indian scientist working in India has been able to emulate his feat.

CV Raman

Other than the pioneering work of Bose — which today would be called biophysics — more conventional biological research took off to a slower start. Birbal Sahni, himself the son of an eminent radiochemist and social worker, pioneered the study of palaeobotany in India, identifying numerous species of fossilised trees, and applying his findings to archaeology, geology and numismatics. Even more influential was the botanical work of E.K. Janaki Ammal, who is credited with developing high-grade sugarcane, now universally grown and probably the origin of the sugar in your next cup of tea. She overcame enormous hurdles of caste and gender discrimination to become India's top agriculturist, developing, among other things, a rounder and juicier hybrid aubergine (brinjal), which is also widely cultivated today.

Janaki Ammal

Two research institutes were started in India during the colonial period. The first was the Indian Association for the Cultivation of Science, founded in 1876 by a homeopathic physician named Mahendra Lal Sarkar. It was here that Sir J.C. Bose would demonstrate his novel experiments, and here it was that Raman and Krishnan discovered the Raman effect. At the other end of the country grew

Jamsetji Tata

IIT Roorkee

a different kind of institution. It arose out of a chance encounter of industrialist Jamshetji Tata with religionist Swami Vivekananda on a ship bound from Yokohama to Chicago. The *swami* and the *seth* struck up a close friendship, in the course of which the former advised the latter to found a testing laboratory in India for mineral ores such as the ones he was carrying abroad with so much pains just for testing. Tata took this advice seriously and earmarked one half of his enormous personal fortune for this purpose — but he died before the new institute could see the light of day. It was actually set up by his sons Sir Dorabji and Sir Ratanji, who really built up the Tata Sons group of industries, at Bengaluru. Today the Indian Institute of Science (IISc) is India's leading academic institute where science and technology, pedagogy and research, make for a winning combination. However, even today, you need to tell the taxi-driver to take you to the Tata Institute.

Upendra Nath Brahmachari

Technical education had, however, started much earlier in India with the College of Engineering, Guindy (1794) at Madras, followed by the Thomason College of Civil Engineering (1847), now the IIT Roorkee, the Bengal Engineering College (1956), now the IIEST, at Shibpur near Kolkata and the Poona Engineering College (1858). The Victoria Jubilee Technical Institute (VJTI) was founded near Bombay in 1887, and it produced India's most iconic engineer, Sir Mokshagundam Vishveshwaraya. Today, Vishveshwaraya is mostly remembered for having thrown the Krishnarajasagar Dam over the river Cauvery and designed the Brindavan Gardens from its runoff waters. But he also performed difficult feats like bridging the river Ganga at Mokameh Ghat, and even at the age of 90, was providing consultancy on how to build the Hirakud Dam across the turbulent river Mahanadi. Another brilliant engineer of the colonial era was Ardaseer Cursetji Wadia, a ship-builder and polymath who may be credited with having brought the Industrial Revolution fairly into India. He was also the first Indian Fellow of the Royal Society of London, hitherto a closed society of British savants.

The Calcutta Medical College was founded in 1835 and the Grant Medical College at Bombay in 1845. It was at the latter that Waldemar Haffkine discovered a vaccine for Asiatic cholera (1897). The French founded an *Ėcole de Médicine* at Pondicherry in 1823; it was re-purposed and renamed the JIPMER in 1964. Colonial India produced many first-class medical men like Sir Ronald Ross (discoverer of the malaria parasite, who was born in India and made his great discovery in Calcutta), Sir Nil Ratan Sarkar, Sir Radha Gobind Kar, Sir Upendra Nath Brahmachari (discoverer of *urea stibamine*, cure for leishmaniasis or *kalazar*), Acacio Viegas (whose timely warning saved Bombay from the worst ravages of the bubonic plague in 1896), Bhau Daji Lad (a polymath as well as a physician), Sakharam Arjun and Bidhan Chandra Roy.

The first Indian woman to get a medical degree was Anandibai Joshi, but she died early, aged 22. Hard on her heels were Kadambini Ganguly, who overcame much prejudice to establish a successful medical practice in Calcutta, and Chandramukhi Bose, who later became the first woman principal of Bethune College. They were followed by Rukhmabai Raut, who also pursued a full medical career in Surat and Rajkot.

Finally, we must recall the greatest mathematical genius India – perhaps the world – has ever produced, and that was Srinivasa Ramanujan. His story has been recently re-told in a book and film entitled '*The Man Who Knew Infinity*'. Ramanujan's phenomenal mathematical intuition led him to fill his notebooks with formulae and theorems which are even now being proved correct, even though a century has elapsed after his early death, aged but 32. No one knows how he obtained them. So amazing is Ramanujan's oeuvre that one might even think of him was a time-traveller from a future, more mathematically-learned, age.

Srinivasa Ramanujan

Independence and Institutions

Anandibai Joshi

On August 15, 1947 came Indian Independence, for a subcontinent immersed in illiteracy, plagued with poverty, divided over doctrine and seething with sectarian fury. The strong pillars of British academia were no longer there to support Indian scientists. Nor were the imposing, but oppressive institutions of the British *raj*. It was a time, therefore, to build, to create, to forget and to innovate. Nothing better expresses the spirit of those times than the stirring words of the long-dead Anandibai Joshi — "*The meanest are those who never attempt anything for fear of failure. Those who begin, and are disheartened by the first obstacles, come next; but those who begin, and persevere through failure and obstacles, are those who win*."

The end of World War II, which preceded Independence by two years, marked the biggest watershed in the nature of scientific research since the Industrial Revolution. Science had, so to speak, proved its worth in the War effort, whether it was radar or code-breaking or the atomic bomb, to say nothing of the effects of penicillin. With this came a new respect and a willingness to spend money on science from governments. The success of the atom bomb project had underlined the utility of collective scientific activity underpinned with liberal financing. This success inspired an increasing corporatisation of science, until alas! we have reached a point today where discoveries are identified as products and scientists have degenerated from 'natural philosophers' to mere 'research workers'!

Independent India moved with the times, in so far as the finances and human resources of the new state would permit. The voices of grassroots-science advocates like Meghnad Saha were drowned in the hammering out of glittering new ivory towers where science could flourish unimpeded in a fledgling nation. Some of these enterprises and their leaders are mentioned below.

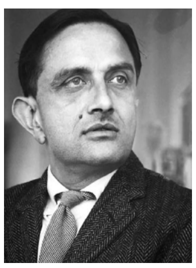
Even before independence, the Tata Institute of Fundamental Research (TIFR) had been founded by a brilliant Cambridge-trained Parsee physicist, Homi Jehangir Bhabha, at Bombay. Bhabha went on to found the Atomic Energy Commission and was tasked with building up a programme of atomic energy generation in independent India by the first Prime Minister, Pandit Jawaharlal Nehru. The Department of Atomic Energy (DAE) was founded in 1954, and the programme has proceeded apace. Even though Bhabha died tragically in an air accident in 1966, the DAE has built energy-generating reactors and also


Homi Bhabha

tested nuclear explosive devices twice, in 1973 and in 1998, bringing India into the select club of nuclear-armed states, albeit with a firm 'no-first-use' policy.

Homi Bhabha's *alter ego*, Vikram Ambalal Sarabhai, also Cambridge-trained, founded the Physical Research Laboratory in Ahmedabad (1947) and went on to found the Indian space programme, which was incubated in TIFR, starting 1962, but soon developed its own facilities. Sarabhai, too, died untimely, aged 52, but that has not prevented India from sending rockets to the Moon and Mars. It was also this expertise in rocketry that enabled the late Abdul Kalam to set up the Indian missile programme, a key factor in India's strategic capabilities in today's world.

The Board (later Council) of Scientific & Industrial Research (BSIR), was founded in 1940 by the London-returned chemist Sir Shanti Swarup Bhatnagar and by Arcot Ramaswamy Mudaliar, the then *Diwan* of the Mysore State. In 1943, Bhatnagar set up five laboratories – the National Physical Laboratory (NPL, Delhi), the Glass and Ceramics Research Institute (GCRI, Calcutta), the National Chemical Laboratory (NCL, Poona), the Fuel Research Station (FRS, Dhanbad) and the National Metallurgical Laboratory (NML, Jamshedpur), using a grant of Rs. 1 crore from the Government and Rs. 20 lakhs from the Tata Industries. Since then, the CSIR's laboratories have proliferated and today there are 38 of them, the latest having been founded in 2021. Bhatnagar died in 1955 and is commemorated by the Shanti Swarup Bhatnagar Prize for Science and Technology — often abbreviated as Bhatnagar Award — which is India's most prestigious recognition for research in S&T fields.


Vikram Sarabhai


SS Bhatnagar

Daulat Singh Kothari, a student first of Meghnad Saha and then of Ernest Rutherford, together with Ramesh Chandra Majumdar, built up the Department of Physics and Astrophysics at Delhi University, where they produced brilliant students like Jogesh Chanda Pati and Suraj Narayan Gupta. Kothari was also instrumental in building up the Defence Research and Development Organisation (DRDO), which has resulted in India being able to build its own aircraft carrier, the new INS *Vikrant*, which was commissioned but recently.

Agricultural research, pioneered by Janaki Ammal, came into its own thanks to the work of Mankombu Sambasivan Swaminathan (b. 1925), whose development of high-yielding varieties of potato, rice and wheat triggered the so-called '*Green Revolution*'. With this came an end to the famines that would affect some part of India every year from immemorial times. In parallel with this, Verghese Kurien, a nuclear physicist turned dairy farmer, set off the '*White Revolution*' by founding Amul, with the aim of bringing hygienic milk to every door in the country. To promote national health, the Minister for Health in the first Cabinet of free India, *Rajkumari* Amrit Kaur (of Patiala State) set up the first All-India Institute of Medical Sciences (AIIMS) in Delhi, donating her own house for this purpose. There are now AIIMS units all over the country, and they play a major role in medical education and in providing quality healthcare to the people.

Darashaw Nosherwan Wadia was a geologist *par excellence*, who studied the stratigraphy of the Himalayan ranges. He founded the Himalayan Institute of Geology at Dehradun in 1968, which is now named after him. Wadia worked closely with Homi Bhabha in surveying post-Independence India and identifying deposits of uranium and thorium, which could feed India's nascent atomic energy programme.

The 'Father of Statistics in India' was Prashanta Chandra Mahalanobis, a contemporary of S.N. Bose and Meghnad Saha. Initially trained as a theoretical physicist, he returned from Cambridge to teach at the Presidency College, where he was taking a course in Einstein's theory of General Relativity within two years of its publication. His real love, however, was statistics, where he had been inspired by reading the British journal *Biometrika*. He started applying statistics to various areas of science, and discovered the metric (or Mahalanobis distance) while making a study of the caste system in India. Mahalanobis went on to found the Indian Statistical Institutes (1932). After Independence, he was made a member of the Planning Commission and in this role, he was the mastermind behind the Second and Third Five-year Plans which undertook the industrialisation of India. To this day, his blueprint is referred to by experts as the 'Mahalanobis Plan'. Incidentally. Mahalanobis was also the first to bring in and set up an electronic computer in India.


Rajkumari Kaur

Before ending this tally, we must not forget the Indian Institutes of Technology or IITs, the proud temples of modern Indian education, which stand tall today among the decay and degeneration of the old University system. It was Sir Ardeshir Dalal, a former chairman of Tata Steel, who, while on the Viceroy's Executive Council in 1945, proposed to set up a set of MIT-style educational institutions to train engineers and technocrats for the soon-to-be free country. This idea was further fleshed out by a committee chaired by a noted Bengali philanthropist-statesman, Sir Nalini Ranjan Sarkar. The Sarkar Committee report was submitted in 1950 and the foundation of the IIT Kharagpur followed in 1951, with eminent chemist Sir J.C. Ghosh (back to Dr. J.C. Ghosh according the newly-minted Constitution) as Director. It was Ghosh who then steered the IITs Act of 1956 through Parliament and ensured that the IITs were declared Institute of National Importance in 1961. By then, four new IITs had come up – at Bombay, Madras, Kanpur and Delhi respectively. Today there are 23, at least one in every major state.


DN Wadia


PC Mahalanobis


J.C. Ghosh

Epilogue

The story of Indian scientists and their achievements after Independence deserves a different article on its own. There one could write about G.N. Ramachandran and S. Chandrasekhar, about A.K. Raychaudhuri and P.C. Vaidya, about S. Bhagavantam and S. Pancharatnam, about T.V. Ramakrishnan and C.K. Majumder, about P.L. Kapurand S.N. Gupta, about Asima Chatterjee and Anna Mani,about the unfortunate Subhas Mukhopadhyay, about major experimental efforts like the Kolar Gold Field Experiment, the Giant Metrewave Radio Telescope and the AstroSat — all of which indicate the maturing of Indian science. It is true that there are many questions still to be answered and many hurdles still to be overcome. Yet, even if the bubbling enthusiasm and firm determination of the new nation may have become a bit jaded after 75 years, it needs but one last push to place India among the developed nations so far as science is concerned. And that is a consummation to be fervently desired.

Sreerup Raychaudhuri is Dean (Academic) and Professor of Physics at TIFR, Mumbai

GNR - A TRIBUTE

D. BALASUBRAMANIAN

When a man comes out with one original idea he is called brilliant. With two he is thought to be extraordinary, but one who comes out with three independent and original ideas is a genius. Einstein, Newton, Pauling and Crick are some examples, and I should like to believe that Gopalasamudram Narayana Iyer Ramachandran, or GNR as he was called by everybody, belonged to this class. He had at least three independent and original ideas to his credit, each of which moved the field that he was engaged in. His first was the elucidation of the structure of collagen. His second was to show what shapes a protein chain can take on, and what it cannot. His third major idea was to show how the three dimensional shape of an object can be reconstructed from a series of flat (or 2-D) pictures using methods of convolution, an idea of value in imaging and tomography.

GNR was born on the 8th of October 1922 in an era in India that was fermenting with ideas, vision and hope for the future. The Independence Movement had gathered momentum, education was valued highly not only for enriching the mind and the soul but also towards enriching the nation itself. There were scholars not only in science and technology but also in literature, arts, politics, law, medicine and engineering. They all had just one common goal for which they worked, namely, an independent strong and resurgent India. In many ways the family GNR came from represented the *zeitgeist* or the spirit of the times. His father, Narayana Iyer, was a professor of mathematics and later the Principal of the Maharaja's College in Ernakulum. GNR had his early education there and later obtained his BSc Honors in physics at the legendary St. Joseph's College, Trichy. He then went to the Indian Institute of Science at Bangalore, and did his MSc by research with C.V. Raman, and continued on with him. In 1947 he won the '1851 Exhibition Scholarship,' which took him to England where he spent the years 1947-49 working in the group of Lawrence Bragg. After his PhD from Cambridge, he returned to the Indian Institute of Science, Bangalore where he taught during 1949- 1952. It was during this time that the classic review on optics was written by him along with S. Ramaseshan.

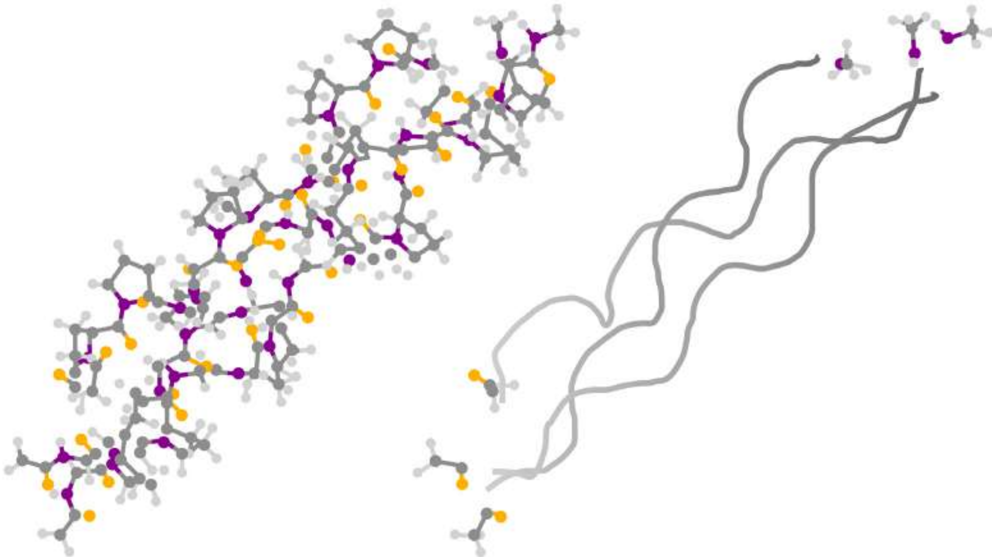
G.N. Ramachandran with his wife Rajalakshmi. Credit: Resonance, Vol.6, No.10, 2001

The Madras Helix

Ramachandran had by this time decided to work on the structure and shape of biological molecules. The late 1940s and early 1950s were a time of great excitement in biology particularly in the newly developed area called biophysics. The elucidation of the spatial disposition of atoms in molecules became possible, thanks to the method called X-ray diffraction. It was becoming increasingly exciting and challenging with the result that people like the Braggs, J.D. Bernal, W.T. Astbury and others mounted a programme to analyze the molecular structures and three dimensional architecture of molecules as large as proteins and nucleic acids. Across the continent it was Linus Pauling in California who was also very active in the X-ray structure determination of proteins. During these eventful years Ramachandran moved from Bangalore to become Professor and Head of the Department of Physics of the University of Madras in 1952, until 1970. It is important to point out here the help and assistance provided to him by A. Lakshmanaswamy Mudaliar who was the Vice Chancellor of Madras University at that time. Ramachandran also had this wonderful proximity to the Central Leather Research Institute and Y. Nayudamma there. When Ramachandran moved to Madras, a ready source of pure animal collagen was made available to him, thanks to Nayudamma. Set with this and armed with excellent colleagues such as Gopinath Kartha and G.K. Ambadi, Ramachandran set out to meet the challenge of determining the 3-dimensional architecture of the protein collagen. Success came within a few years and the prototype of the currently accepted structure of collagen was first put forward in 1954 by Ramachandran and Kartha in a paper published in the journal *Nature*. If the alpha helix were the California helix and if the double helix were the British helix, the collagen helix came to be known as the Madras helix.

The Ramachandran Diagram

Many people would have felt a sense of fulfillment after such a major discovery but not Ramachandran. What factors go to govern the myriad shapes that protein and polypeptide chains adopt was a question that enticed him. To this end, he asked his students, notably V. Sasisekharan and C. Ramakrishnan, to analyze all X-ray diffraction pictures published until then on amino acids, peptides and proteins and to find out what sets of bond angles and shapes they most often take. They were soon able to write out the entire conformational space that a polypeptide chain can occupy. It was done in much the same manner that cartographers do when they write out maps, based on two coordinates. These two coordinates in proteins are referred to as dihedral angles, and named after the Greek letters *phi* and *psi*. This analysis has come to be known in protein science as the celebrated Ramachandran map or the Ramachandran diagram. It is indeed a tribute to Ramachandran that each one of the over 10,000 protein structures that has been so far solved obeys the principles and the allowances of the Ramachandran map. Ramachandran was thus able to give a conformational grammar to protein structure. This was his second achievement. Sasisekharan extended the conformational map to DNA chains, and V.S.R.



The Collagen Triple Helix. Graphic by Roshni Samuel

Rao did so for sugar chains. The folding rules of these three biopolymer chains had thus been established by the GNR school.

His mentor C.V. Raman immortalized himself in physics through the Raman effect, and GNR has immortalized himself in biophysics and biochemistry with the Ramachandran diagram. Indeed, when one looks at contemporary scientists of India, no one else has had such recognition in professional literature and textbooks as Raman and Ramachandran. Many people in the profession have felt that these two achievements, namely the elucidation of the structure of collagen and providing a grammatical basis for the three dimensional shapes that a biopolymer chain can adopt, would suffice for award of the Nobel Prize. They both have stood the test of time, have helped us advance our knowledge not only in structure but also in the function of protein chains, and have opened up newer ways of designing molecules. It is indeed a pity that Ramachandran was not awarded the Prize, and never will be, now that he is no more. Nobel Prizes in biology have been given for lesser achievements, and it will remain a sour point, at least in my mind, that Ramachandran was not. It may justifiably be said that in this case that it is the Prize who missed the master.

The I8-year period that Ramachandran spent at the University of Madras was a golden era. Together with Alladi, who was a Reader, he brought forth a department that produced gems as students, excellence breeding excellence. It is worth reflecting on what made this magic possible. First is surely the man behind it and the passion that he had for academic brilliance (despite a slowly debilitating illness that started affecting him already). Second is the ability to choose students and colleagues, and the freedom to recruit them. Third is understanding and appreciation by the administrators, and their willingness to enable this to happen. It was here that Vice-Chancellors with vision such as Mudaliar and neighbours with ready help such as Nayudamma become vital. How I wish we find modes to make their tribe increase!

Mudaliar left the University and the anchor of support to GNR weakened. Rule books were thrown at him, and he left the University in a huff. Here that we must record our appreciation to two other men of vision and foresight namely Satish Dhawan and S. Ramaseshan, who invited GNR to return to Bangalore and start the Molecular Biophysics Unit (MBU) at the Indian Institute of Science, Bangalore. Sasisekharan, Ramakrishnan and V.S.R. Rao went along with him to the MBU, added more people and helped the MBU become a globally respected centre in biophysics.

Despite his progressively weakening illness (later identified as Parkinson's), GNR continued to be active, this time in area of mathematical logic. Having handed MBU over to able hands, he switched to this field and published a series of papers on what he called as *Syad* and *Nyaya* logic, reminiscent of and akin to what today is called fuzzy logic. But, alas, his illness weakened him and he suffered for over a decade before he passed away.

(Reproduced with permission from *Resonance*, Vol.6, No.10, pp-2-4, 2001)

D Balasubramanian is the former President of the Indian Academy of Sciences and director of research at the Prof. Brien Holden Eye Research Centre of L. V. Prasad Eye Institute, Hyderabad

EDITOR'S NOTE:

G.N. Ramachandran, one of India's most brilliant minds, made lasting contributions to biology and physics. At ICTS-TIFR, one of our three academic blocks is named after GNR. The other two are named after Harish-Chandra and Abdus Salam. During GNR's centenary year, *ICTS News* celebrates his life and work with two tributes.

GNR- THE FIRST TEN YEARS

RAJARAM NITYANANDA

This is an account of G.N. Ramachandran's (GNR's) work, largely on optics (including the optics of X-rays in crystals) in the first decade of his scientific journey, 1942-1952. This would have been considered outstanding coming from any other person, but is dwarfed in impact by the later work on biophysics. There is a connection, however, acknowledged in the dedication to the monograph *Fourier Methods in crystallography* which he co-authored with R. Srinivasan. It reads *"To the Leader of Modern Indian Science, Professor C.V. Raman, who initiated the senior author into the mysteries of diffraction theory and Fourier transforms."*

Indian Institute of Science 1942-47

Almost every paper written during the period 1942-1947 acknowledges the influence of Raman – and not one has Raman as co-author! GNR's brilliance and independence must have been evident from day one. He joined the physics department in October 1942. Legend has it that the delay of three months is due to a short stint in Electrical Engineering, which only ended when Raman told the head of that department that this boy is too intelligent to work in your field (!). The very first problem Raman gave him was reflection from a periodic array of plates, already addressed by Rayleigh. In a week, GNR came up with a very original way of looking at it, which was published as a single author paper in the Proceedings of the Indian Academy of Sciences before the year was out. Entering with a BSc honours from St. Joseph's college in Tiruchirapalli, he soon got an MSc by research, which the thesis examiner (K.S. Krishnan, no less!) said was already at the PhD level. He appears to have taken the track to a DSc which came in five years. In those days, this was considered one level above a doctorate since the work had to be independent and substantial. During this period, he carried out extensive theoretical, experimental and numerical studies on optical and other properties of crystals, diffraction of light and of X-rays. Some of the highlights are listed below: The periodic array of plates in optics, the subject of GNR's first paper, also models the interaction of X-rays with layers of atoms in a crystal. He worked out a large number of cases of interest and derived earlier results of Darwin's 'dynamical theory' of X-ray diffraction from his formalism. Dynamical refers to the fact that each layer sees not just the incident wave but that reflected by all other layers.

The MSc thesis was a study of a variant of "Christiansen experiment." Spherical drops in an emulsion were illuminated. At a particular wavelength, the refractive index of the drops matched that of the surrounding liquid and there is no scattering. Changing the wavelength in either direction gives a controlled, wavelength dependent mismatch, which causes scattering with beautiful colours. The thesis developed the quantitative theory of his own experiments.

Classical aspects of diffraction were touched and enriched in his work. Going back to Fresnel and Young, two equivalent formulations already existed, one summing up waves originating from the entire area of the aperture, and the other just from the perimeter. Raman made the observation (in the literal sense, through an eyepiece!) that only a few points on the edge seem to dominate. GNR developed this into a systematic theory bringing order to the apparently complex patterns produced by apertures of different shapes. The idea was reborn in the 1960's as a rigorous geometric theory of diffraction, used even today as a short wavelength approximation by engineers.

On another front, the Fraunhofer (far-field) diffraction pattern of a large number of particles, randomly distributed on a glass slide was studied. The spores of *Lycopodium* provide a convenient source of circularly symmetric objects of uniform size.

It was long known that the pattern shows the rings characteristic of a single circular obstacle, when viewed at low resolution. GNR measured the microstructure and statistics of the random intensity fluctuations, within each ring, nowadays known as 'speckles'. This had to be from photographs – no easy task. One striking result from the experiment and the theory was that each speckle gave an image of the illuminating aperture produced by a seemingly random 'lens.' This result presaged an important application made decades later in optical

G. N. Ramachandran (1922 - 2001)

astronomy. High angular resolution is possible in spite of random phases introduced by a turbulent atmosphere, so long as the exposure time is short enough to freeze the speckles.

Raman's fascination for diamond rubbed off on GNR as well. The X-ray diffraction spots of some specimens revealed some surprising features. GNR observed these systematically, at lightning speed, and interpreted them in terms of the 'dynamical' theory already described earlier, taking due account of small but crucial deviations from crystal perfection. In the process, he invented 'topography,' a tool used ever since to map out subtle imperfections in crystals, in particular silicon, the workhorse of the semiconductor industry.

Cambridge 1947-49

Winning the prestigious 1851 Exhibition Research Fellowship, GNR spent two years at the legendary Cavendish Laboratory of Cambridge University. He was in the crystallography laboratory headed by the Nobel Laureate W.L. Bragg. The fellowship did not require working for a degree but GNR chose to enrol for a PhD with W.A. Wooster.

This work brought out his theoretical and experimental powers. Recall that the periodic arrangement of atoms in a crystal gives rise to the sharp, 'Bragg' peaks in the X-ray diffraction pattern which are of course the key to deducing the arrangement of atoms in the unit cell. These peaks are surrounded by diffuse scattering, which is caused by the deviations from strict periodicity, due to the thermal motions of the atoms. This was measured quantitatively using a Geiger Counter, and modelled to infer the elastic constants of the crystals under study. Put simply, the stiffer the crystal, the harder it is to create short wavelength vibrations at a given temperature, so that the diffuse scattering falls off more sharply as we go away from the central peak. GNR developed the necessary theory. Since the properties of sound waves depend on direction in a crystal, this study can reveal the anisotropy of the elastic constants.

As a spin off, papers with Wooster and Lang appeared in the Review of Scientific Instruments, describing methods for bending a crystal to focus the x-rays and gain a crucial five-fold increase in the counting rate. Separate work with P.B. Hirsch, dealt with intricacies of X-ray diffraction from nearly perfect and absorbing crystals. All this in two years!

Perutz, Kendrew, and of course Bragg, were the luminaries of the Cambridge crystallography group at that time. They were establishing a base camp for the assault on the crystal structure of proteins - in particular myoglobin and haemoglobin. As D. Balasubramaniam's article brings out, GNR's own enduring contributions after 1952 were precisely in the same area – the structure of biological molecules. He must surely have absorbed the excitement and importance of this field during his stay, though it is not reflected in any publication. He later mentioned drawing great inspiration from a visit by Linus Pauling (rather than the locals, one might add).

Indian Institute of Science 1949-52

GNR returned to the physics department of the IISc in 1949, as a young assistant professor. He soon set up a crystallographic laboratory, with a counter, for quantitative measurements, concentrating initially on the physics of X-ray diffraction from crystals rather than structure determination.

One collaboration in optics during this period stands out. It was with S. Ramaseshan (SR), who had joined Raman in 1943, only nine months after GNR. He relates how GNR had the complete theory of separating the effects of birefringence and Faraday rotation worked out by the next morning, after their discussion! Their work utilised the geometric representation of polarised light due to Poincare, and seems to have caught wider attention.

The 'Handbuch der Physik,' a bible of the pre-war period, was still reputed in the 1950's for scholarly and authoritative reviews. The editors invited GNR and SR to cover all of crystal optics. Their comprehensive review article, very much in the German Handbuch tradition, appeared in 1961. Gopinath Kartha, GNR's first research student, joined him at IISc and started work on crystal structures of barium chlorate and morellin.

Kartha moved with GNR to Madras, and the rest is history – they climbed the Everest of the collagen structure.

Going by the early papers, and contemporary accounts, there is no doubt that a star burst upon the scene in 1942. There is much to appreciate in GNR's work over these ten years but in retrospect, it seems like a period of gestation. One can draw a parallel to Raman's own early work on the acoustics of musical instruments - both were just flexing their muscles. Apparently Rutherford asked Raman in 1921 why he chose to work on fiddlesticks (Raman had a major study of the violin!).

The record shows that Raman turned to light scattering soon after that. GNR's early work on light and X-rays is certainly deep, but history shows that he needed a space of his own to really soar to the heights that he attained. Lakshmanaswami Mudaliar will be remembered for inviting him to Madras, University, even as Ashutosh Mukherjee is remembered for inviting Raman to the Calcutta University. Such scientists and such Vice Chancellors are hard to come by.

Rajaram Nityananda is Simons Visiting Professor of Physics at ICTS-TIFR, Bengaluru.

GNR image credit: Current Science, VOL. 80, NO. 8, 25 APRIL 2001

BETWEEN THE SCIENCE

SUBHRO BHATTACHARJEE and AJITH PARAMESWARAN were selected as members of the National Academy of Sciences, India (NASI).

ICTS graduate student JUNAID MAJEED BHAT was awarded the inaugural pan-TIFR "Prof. S. Naranan Memorial Research Award."

RAMA GOVINDARAJAN received the IIT Delhi Distinguished Alumni Award in recognition of her achievements in teaching and research.

RAMA GOVINDARAJAN'S publication (in collaboration with Sumithra Reddy Yerasi and Dario Vincenzi of the Université Côte d'Azur, CNRS), titled 'Spirographic Motion in a Vortex' was highlighted as Editor's Suggestion in Physics Review Fluids.

BETWEEN THE SCIENCE

ICTS graduate student PRONOBESH MAITY was selected for the prestigious KITP Graduate Fellowship Program. Pronobesh will be guided by Nobel Prize winner David Gross during his stay at KITP.

SUVRAT RAJU was awarded the 10th Nishina Asia Award 2022, for "the original and influential insights into the resolution of the black hole information paradox and the principle of holography in quantum gravity."

SUMATHI RAO was elected as a Fellow of the American Physical Society. She has been cited "For contributions to transport in low-dimensional interacting systems, especially junctions of more than two wires, edge/surface physics of topological systems, and for contributions to overcoming the under-representation of women in physics."

SAMRIDDHI SANKAR RAY, together with ICTS associates Jason Picardo, Jeremie Bec and Dario Vincenzi, were awarded a CEFIPRA (Indo-French) grant for their joint research.

STHITADHI ROY's publication (in collaboration with Max McGinley and S.A. Parameswaran from Oxford University), titled "Absolutely Stable Spatiotemporal Order in Noisy Quantum Systems," was highlighted as Editors' Suggestion in Physical Review Letters.

ICTS graduate student PRASHANT SINGH's work, done together with his advisor Anupam Kundu, was selected for the Top Cited Paper Awards India 2022 in the mathematical sciences category by IOP Publishing.

JIM THOMAS was awarded a SERB-Early Career Research Grant.

ICTS graduate student ADITYA VIJAYKUMAR was selected for the Fulbright-Nehru Doctoral Research Fellowship. The prestigious fellowship will enable Aditya to work for seven months with astrophysicist Daniel Holz at the University of Chicago.

PROGRAMS

Horizons in Accelerators, Particle/Nuclear Physics and Laboratory-based Quantum Sensors for HEP/NP
14-17 November 2022 ✦ *Organizers* — Organizers: Swapan Chattopadhyay and Rohini Godbole

Statistical Biological Physics: from Single Molecule to Cell
17-28 January 2022 ✦ *Organizers* — Organizers: Debashish Chowdhury, Ambarish Kunwar and Prabal K Maiti

Tipping Points in Complex Systems (Hybrid)
19-30 September 2022 ✦ *Organizers* — Partha Sharathi Dutta, Vishwesha Guttal, Mohit Kumar Jolly and Sudipta Kumar Sinha

Frustrated Metals and Insulators (Hybrid)
5-16 September 2022 ✦ *Organizers* — : Federico Becca, Subhro Bhattacharjee, Yasir Iqbal, Bella Lake, Yogesh Singh and Ronny Thomale

Nonperturbative and Numerical Approaches to Quantum Gravity, String Theory and Holography (Hybrid)
22 August-2 September 2022 ✦ *Organizers* — David Berenstein, Simon Catterall, Masanori Hanada, Anosh Joseph, Jun Nishimura, David Schaich, Toby Wiseman

Elliptic Curves and the Special Values of L-Functions (Hybrid)
8-19 August 2022 ✦ *Organizers* — Ashay Burungale, Haruzo Hida, Somnath Jha, Ye Tian

First-Passage Percolation and Related Models (Hybrid)
11-29 July 2022 ✦ *Organizers* — Riddhipratim Basu, Jack Hanson, Arjun Krishnan

Bangalore School on Statistical Physics - XIII (Hybrid)
11-22 July 2022 ✦ *Organizers* — Abhishek Dhar, Sanjib Sabhapandit

Combinatorial Algebraic Geometry: Tropical and Real (Hybrid)
27 June-8 July 2022 ✦ *Organizers* — Arvind Ayyer, Madhusudan Manjunath, Pranav Pandit

Summer School for Women in Mathematics and Statistics
13-24 June 2022 ✦ *Organizers* — Siva Athreya, Anita Naolekar, Senthil Raani K.S, Dootika Vats

ICTS Summer School on Gravitational-Wave Astronomy (Hybrid)
30 May-10 June 2022 ✦ *Organizers* — Parameswaran Ajith, K. G. Arun, Bala R. Iyer, Prayush Kumar

Physics with Trapped Atoms, Molecules and Ions (Hybrid)
9-13 May 2022 ✦ *Organizers* — Bimalendu Deb, Sourav Dutta, Saikat Ghosh

DISCUSSION MEETINGS

Structured Light and Spin-Orbit Photonics
29 November-2 December ✦ *Organizer* — Thierry Dauxois, Sylvain Joubaud, Manikandan Mathur, Philippe Odier, Anubhab Roy

Particle Physics: Phenomena, Puzzles, Promises
15-18 March 2022 ✦ *Organizers* — Amol Dighe, Rick S Gupta, Sreerup Raychaudhuri and Tuhin S Roy

Mathematics Teachers Training Camp at ICTS
4-7 November 2022 ✦ *Organizers* — Prithwijit De (HBCSE-TIFR, India) and Pranav Pandit (ICTS - TIFR, India)

The Future of Indian Astronomy (Hybrid)
31 October-2 November 2022 ✦ *Organizers* — Parameswaran Ajith, G. C. Anupama, Dipankar Banerjee, Varun Bhalerao, Poonam Chandra and Divya Oberoi

Targeted Questions in Condensed Matter (Online)
22 September 2022 ✦ *Organizers* — Subhro Bhattacharjee (ICTS - TIFR, India), Arun Paramekanti (University of Toronto, Canada) and Nandini Trivedi (The Ohio State University, USA)

L-functions, Circle-Method and Applications (Hybrid)
27 June-1 July 2022 ✦ *Organizers* — Soumya Das, Ritabrata Munshi, Saurabh Kumar Singh

Stochastic Thermodynamics: Recent Developments (Online)
14-17 June 2022 ✦ *Organizers* — Shamik Gupta, Sourabh Lahiri, Arnab Saha

LIGO-Virgo Open Data Workshop
25-26 May 2022 ✦ *Organizers* — Parameswaran Ajith, Soummyadip Basak, Srashti Goyal, Aditya Vijaykumar

Laboratory for Interdisciplinary Breakthrough Science (Hybrid)
25 May 2022 ✦ *Organizers* — Shravan Hanasoge

LECTURE SERIES

INFOSYS-ICTS CHANDRASEKHAR LECTURES

Looking into the Future of High-Energy Particle Physics
November 2022 ✦ *Speaker* — Gian Giudice *(CERN, Switzerland)*

DD KOSAMBI LECTURES

Ancient Mural Paintings of India
11 August 2022 ✦ *Speaker* — Benoy K Behl *(Adjunct Professor at National Institute of Advanced Studies)*

ICTS-INFOSYS STRING THEORY LECTURES

Symmetries in QFT and Their Relationship With Category Theory
16 December 2021 ✦ *Speaker* — Lakshya Bhardwaj *(Mathematical Institute, University of Oxford)*

Supersymmetric Black Holes, the Superconformal Index, and Phases of AdS/CFT
2-5 August 2022 ✦ *Speaker* — Sameer Murthy *(King's College, London, UK)*

TMC DISTINGUISHED LECTURES

Maxwell's Demon Goes Optical!
15 November 2022 ✦ *Speaker* — Swapan Chattopadhyay *(FNAL, USA & IISc, India)*

On the Tensor Product of Representations of Classical Groups
Video release: 3 August 2022 ✦ **Interactive session**: 3 August 2022 ✦ *Speaker* — Lakshya Bhardwaj *(Mathematical Institute, University of Oxford)*

Asymmetry in Dynamics
Video release: 21 June 2022 ✦ **Interactive session**: 14 July 2022 ✦ *Speaker* — Amie Wilkinson *(University of Chicago)*

EINSTEIN LECTURES

Astronomy's New Frontiers
6 October 2022 ✦ *Speaker* — Ajith Parameswaran *(ICTS-TIFR, Bengaluru)*

In Search of Brain Plasticity
5 September 2022 ✦ *Speaker* — Kshipra

Gurunandan *(University of Cambridge, UK)*

OUTREACH

KAAPI WITH KURIOSITY

History of Walking Robots
30 October 2022 ✦ *Speaker* — Shishir N. Y. Kolathaya *(Indian Institute of Science, Bengaluru)* ✦ *Venue* — J. N. Planetarium, Bangalore

Finding Our Place Among Stars
11 September 2022 ✦ *Speaker* — **Sarita Vig** *(Indian Institute of Space Science and Technology, Thiruvananthapuram)*

Simulations: Why, What and How?
28 August 2022 ✦ *Speaker* — Parthanil Roy *(Indian Statistical Institute, Bengaluru)*

Novel Phases of Matter Near Absolute Zero Temperature
31 July 2022 ✦ Speaker — Sanjukta Roy *(Raman Research Institute, Bengaluru)*

Greening of Bangalore
26 June 2022 ✦ *Speaker* — Vijay Thiruvady *(Bangalore Environment Trust)*

(From top) ICTS members celebrating Onam. Benoy K Behl delivering the DD Kosambi Lecture titled, *Ancient Mural Paintings of India*. Parthaniel Roy during his Kaapi with Kuriosity lecture titled, *Simulations: Why, What and How?* Sarita Vig during her Kaapi with Kuriosity lecture titled, *Finding our Place Among Stars*.

ICTS INTERNATIONAL CENTRE for THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

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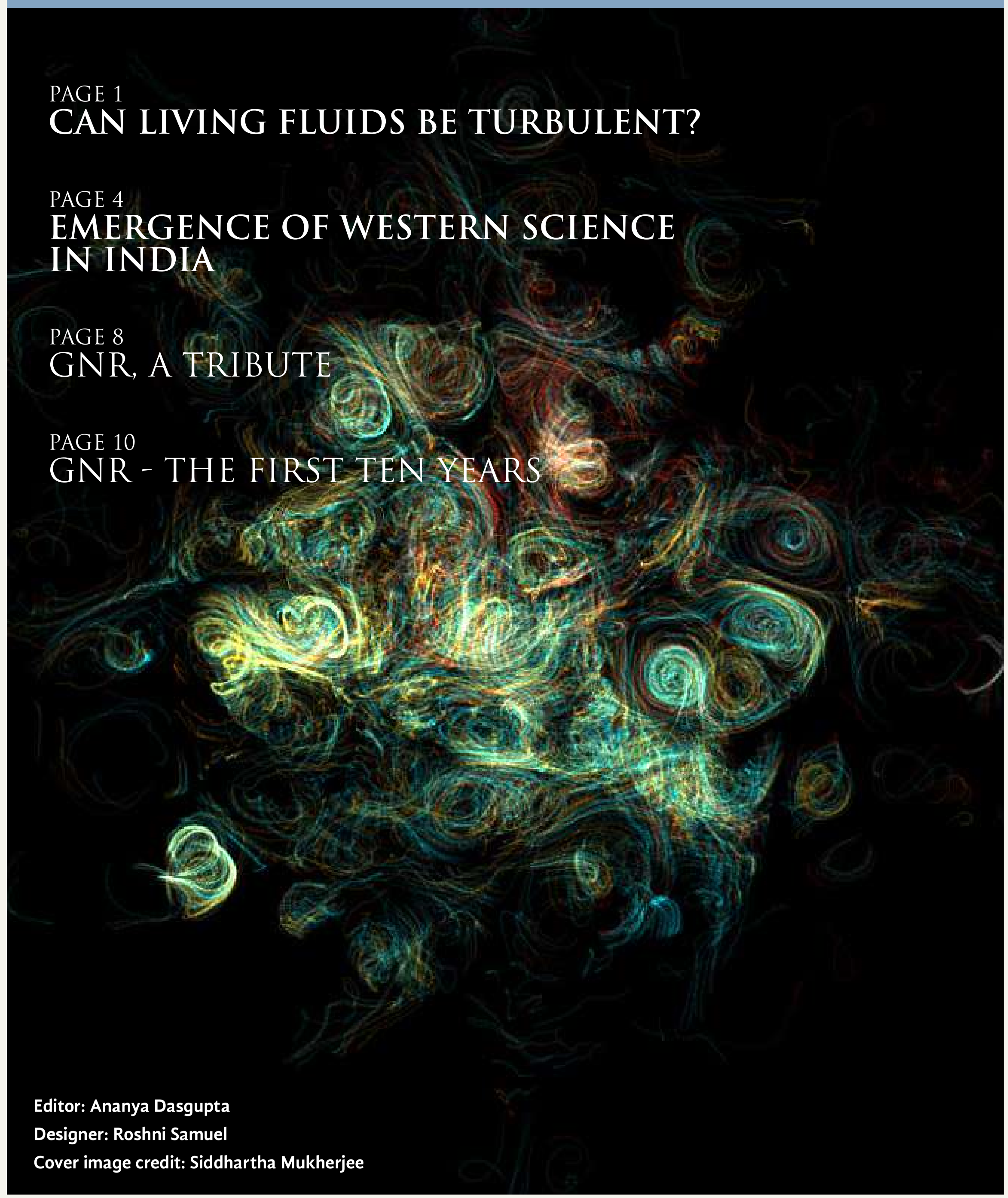

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